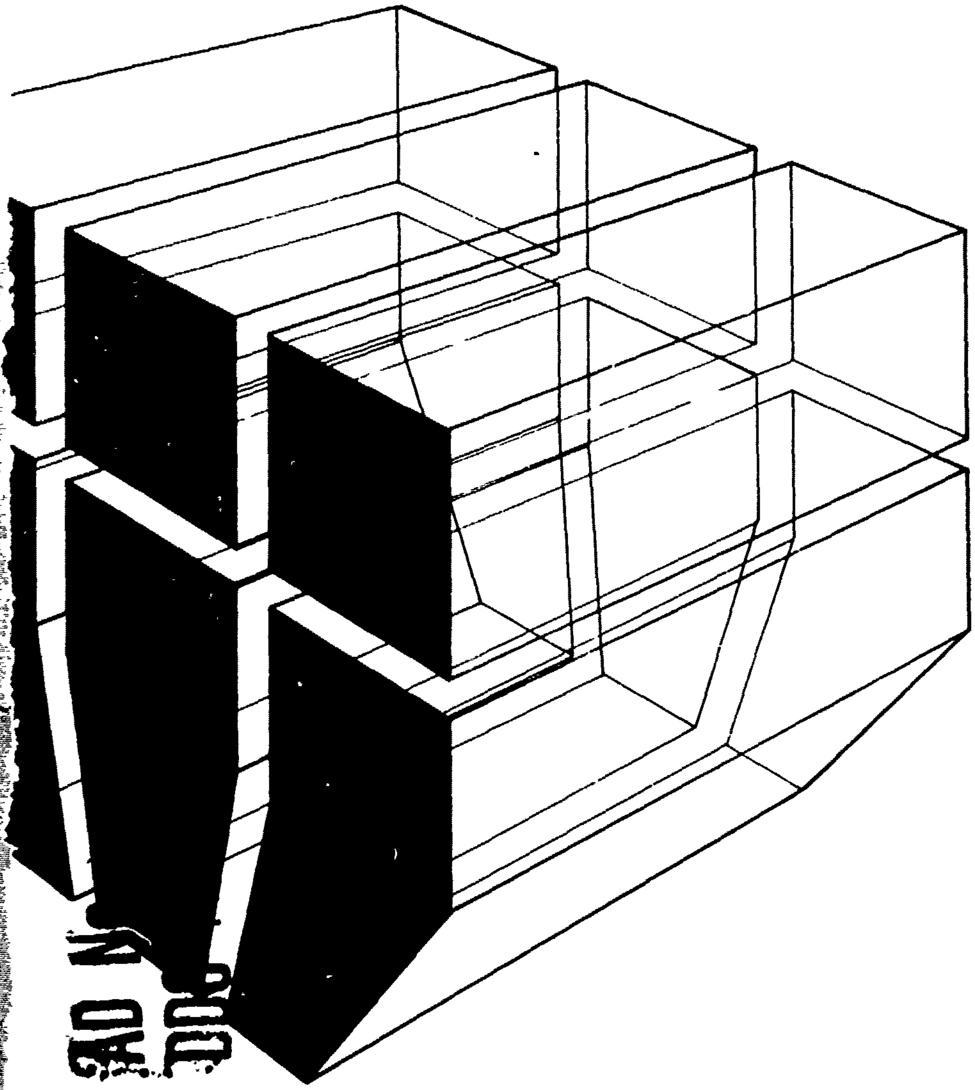
construction
engineering
research
laboratory

12

B5

INTERIM REPORT E-110
July 1977
Waste-Derived Fuel Utilization Manual

TECHNOLOGY EVALUATION OF ARMY-SCALE WASTE-TO-ENERGY SYSTEMS



by
S. A. Hathaway
R. J. Dealy

CERL

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER (14) CERL-IR-E-110 ✓

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER (9)

4. TITLE (and Subtitle) (6) TECHNOLOGY EVALUATION OF ARMY-SCALE WASTE-TO-ENERGY SYSTEMS.

5. ~~TYPE OF REPORT & PERIOD~~ COVERED INTERIM rept.,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s) (10)
S. A./Hathaway
R. J./Dealy

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
CONSTRUCTION ENGINEERING RESEARCH LABORATORY ✓
P.O. Box 4005
Champaign, IL 61820

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) 4A762719AT41-T6/011 (17)

11. CONTROLLING OFFICE NAME AND ADDRESS (11)

12. REPORT DATE Jul[redacted] [redacted]77

13. NUMBER OF PAGES 84

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (12) 85p.

15. SECURITY CLASS. (of this report) Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Copies are obtainable from National Technical Information Service
Springfield, VA 22151

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

refuse-derived fuel
pyrolytic conversion
anaerobic digestion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This investigation evaluated current and emerging technologies for ~~the~~ converting ~~sion of~~ waste to energy in applications scaled for use on Army fixed facilities and installations. Technologies reviewed included: mass burning of wastes in package (modular) and field-erected systems; use of refuse-derived fuel (RDF) in new combustion capital and as a supplementary fuel in existing Army-scale central steam generators; pyrolytic conversion of waste to a gaseous and liquid fuel; and anaerobic

(cont on p 2)

405 279

1B

Block 20 continued.

digestion of wastes to a fuel gas. The report includes application of a rating system for candidate technologies which considers dependability, practicability, conservation, environmental compatibility, economics, and length of operational history. Use of package waste-to-energy systems and use of RDF as a supplementary boiler fuel are treated in detail.

It was found that fully satisfactory methods of surveying installation solid waste to determine energy-recovery system design points are lacking, and that currently used methods can result in misapplication of capital. Combustion of unprocessed and minimally processed (once-shredded) solid waste in field-erected integrated waterwall combustors equipped with mechanical stokers is currently the superior energy recovery technology. Anaerobic digestion and pyrolytic conversion were found to be unproven but developing. Predesigned package heat recovery systems have a short operational history (about 2 years) and theoretically will perform better when firing shredded waste rather than unprocessed material. Because of lack of experience, their use engenders more risk than field-erected systems. Use of RDF as a supplementary fuel with coal in existing Army-scale central stoker-fired steam generators is a rapidly developing area with many unknowns. It appears that each candidate boiler must be individually evaluated for its potential to fire the waste fuel, and that generalizations about using RDF on an Army-wide basis cannot presently be made. The investigation showed that if a boiler is to retain rated capacity when firing RDF, it will probably have to be rebuilt to enlarge the furnace volume, with additional modifications of solid fuel handling facilities and plant auxiliaries. Field test and evaluation of those systems having potential Army-scale application is required to precisely determine critical operational parameters.

FOREWORD

This work was performed for the Directorate of Facilities Engineering, Office of the Chief of Engineers (OCE), under project 4A762719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Technical Area T6, "Energy Systems"; Work Unit 011, "Waste-Derived Fuel Utilization Manual," Technical Area T6 supported by QCR 1.03.006 (4). Mr. A. P. Norwood served as the OCE Technical Monitor.

The work was performed by the Energy Systems Branch (EPE) of the Energy and Power Division (EP), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. S. A. Hathaway served as the Principal Investigator for CERL. Administrative support provided by Dr. D. J. Leverenz, Chief of EPE, and Mr. R. G. Donaghy, Chief of EP, is acknowledged.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

CONTENTS (Cont'd)

FIGURES

FIGURES (Cont'd)

TABLES

TABLES (Cont'd)

TECHNOLOGY EVALUATION OF ARMY-SCALE WASTE-TO-ENERGY SYSTEMS

1 INTRODUCTION

Background

The rapidly growing consumption of conventional low-cost energy resources, the annually rising costs to collect and haul installation waste, and the decreasing land volume available for direct landfill disposal are prompting interest in use of waste-to-energy systems at Army fixed facilities and installations. Increasing Army interest is reflected by the growing number of installation proposals to implement currently available energy-recovery technologies.

However, whether recovering energy from waste is economically feasible on a general basis is not yet known. Claims that resource recovery is now universally almost as inexpensive as landfilling, and that investments in pilot resource recovery projects can be recouped in as little as 2 years[1] conflict with warnings that resource recovery is capital-intensive and that careful consideration is warranted before tallying revenues.[2]

Opinions on technical aspects of Army-scale energy-recovery systems are equally as divergent. There are optimistic assertions that currently available but untested energy-recovery technologies scaled for installation use will show virtually trouble-free operation for 10 years from the time they are brought on-line.[3] Those experienced in evaluating equipment for project development and design, however, point out the paucity of the long-term data on operational history needed to precisely predict and guarantee successful performance of such systems.[4]

Implementation of soundly engineered, practicable waste-to-energy systems which perform reliably and predictably could produce benefits to the Army in the form of fuel savings, reduced waste disposal costs, and greater environmental compatibility in waste disposal operations. These potential advantages and the conflicting technical-economic opinions regarding current small-scale waste-to-energy systems were the basis of this investigation into the present technical status of current and emerging energy recovery technologies having potential use at Army installations.

Objective

The objective of this investigation was to evaluate the technical status of current and emerging waste-to-energy technologies which might have potential application on Army fixed facilities and installations in order to provide guidance to the Directorate of Facilities Engineering of the Office of the Chief of Engineers (OCE).

Approach

The investigation followed three discrete but interrelated paths of inquiry:

1. Theoretical and operational data on current and emerging waste-to-energy technologies were compiled through a comprehensive literature review, extensive contacts with manufacturers/vendors, and numerous field observations.

2. Using data collected in Step 1, each technology's potential for installation use was evaluated.

3. A rating system was developed and used to comparatively evaluate the identified technologies.

Organization of Report

Chapter 2 reviews the nature of Army solid waste as it pertains to its potential utilization in energy-recovery systems. The two chief conversion methods, combustion and pyrolysis, are discussed in Chapter 3. Combustion processes were categorized as mass-burning and refuse-derived fuel (RDF) processes; the two categories are discussed separately in Chapters 4 and 5. In both chapters, considerable attention is given to evaluating package incinerator heat-exchange systems because they are more compatible with the smaller scale of waste generation on the typical installation than are field-erected systems. Chapters 6 and 7 discuss pyrolytic and aerobic digestion processes, respectively. Chapter 8

---

[1] N. W. Snyder, "Energy Recovery and Resource Recycling," *Chemical Engineering* (October 21, 1974), pp 65-72.

[2] N. Rueth, "Can America Survive Materials Shortages?", *Mechanical Engineering*, Vol 97, No. 1 (January 1975), pp 29-33.

[3] H. G. Rigo and M. E. Eifert, *Technical and Economic Review of NCRR Grant Application Entitled Preparation, Use and Cost of d-RDF as a Supplementary Fuel in Stoker Fired Boilers* (Systems Technology Corporation, June 1975), pp A1, A2, B1, B2.

[4] *Refuse Incinerator/Heat Reclamation Facility, Naval Station Mayport, FL* (Greenleaf/Telesca, Planners, Engineers, Architects, Inc., 1975), pp V-13 – V-17.

gives the results of a comparative technical/economic rating system applied to all applicable energy-recovery technologies. Conclusions of the investigation are given in Chapter 9, with a discussion of the direction of future work in Chapter 10. The use of RDF in existing Army-scale central steam generators was investigated in detail: this investigation is summarized in Appendix A.

2 NATURE OF ARMY SOLID WASTE

General

Evaluation of the potential of using solid waste as an energy resource at a given installation requires precise identification of the waste's characteristics, including proximate and ultimate analyses, a burning profile, ash characterization, higher and lower heating values, and the mass generation rate of the material. The fuel properties of interest are defined in Chapter 3. The mass generation rate refers to the quantity of solid waste generated daily on an installation and is usually stated in terms of TPD_5 or TPD_7 (tons per day on either a 5- or 7-day per week basis).

It is currently widespread practice to characterize installation solid waste for energy-recovery purposes by conducting a brief collection vehicle weigh survey to obtain an average daily mass generation rate and visually observe the fractional constituency of loads either in collection vehicles or at the disposal point to determine waste composition: subsequent calculations are then performed only with data pertaining to constituency, generation rate, heating value, and ash content. A major assumption underlying this approach is that the daily rate of generation and the constituency of installation solid waste are random. This has spawned assertions that the composite heating value (mass generation rate times heating value) of an installation's waste stream follows a normal distribution,[5] and that actual design points of energy conversion hardware can be obtained quite simply by adding to the average daily heating value some fraction of its standard deviation, which is presumed to be a constant proportion of the average over time.

This chapter discusses problems encountered in using this conventional procedure and the impact it has on project economics. This section also provides a basic background on the nature of Army solid waste only as it pertains directly to energy-conversion processes. Schanche, et al., have previously reviewed the general characteristics of Army solid waste.[6]

Quantification

On an Army-wide basis, approximately 250 million cu yd (191 million m^3) of mixed solid waste was collected and disposed of in fiscal year (FY) 75.[7] Most of this volume was handled on U.S. Army Training and Doctrine Command (TRADOC) and U.S. Army Forces Command (FORSCOM) installations in the Continental United States (CONUS). Assuming a loose bulk density of 100 lb/cu yd (59.3 kg/m^3), a mass of 12.5 million tons (11.3 million MT) of solid waste passed through Army waste disposal operations. Nearly all of this waste was disposed of in as-collected condition by sanitary landfilling within the installations.

Gross Army-wide figures do not indicate the scale of each operation. Figure 1 displays solid waste generation rate data for major FORSCOM, TRADOC, Development and Readiness Command (DARCOM), Health Services Command (HSC), and Communications Command installations in CONUS. Data are in tons per year, computed by using the loose bulk density of 100 lb/cu yd (59.3 kg/m^3). (As shown below, use of a general density conversion factor is strictly incorrect; its application here is only for purposes of general illustration.) Figure 1 illustrates the *scale* of the Army waste-to-energy consideration. Typical municipal-scale waste-to-energy systems process up to 1000 TPD_5 (907 MTPD_5). In contrast, 40 TPD_5 (35 MTPD_5) is a typical generation rate among fully active major Army installations in CONUS.

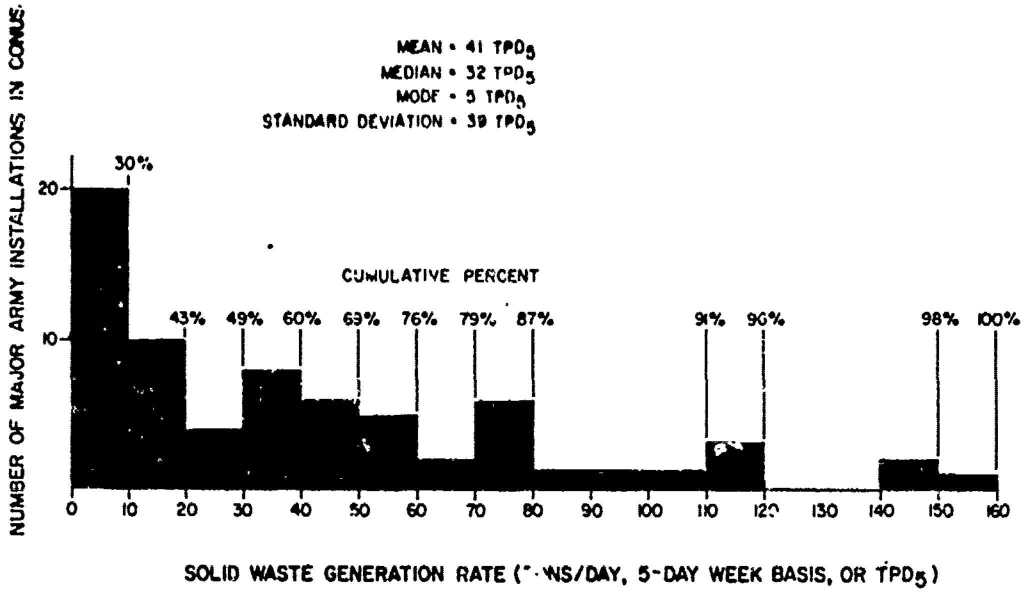
The substantially lower solid waste generation rates typifying Army installations have considerable impact on potential implementation of waste-to-energy systems. Economies of scale are far different than for municipal systems. Moreover, the major

---

[5] H. G. Rigo, "Characteristics of Military Refuse," *Proceedings of the ARPA Workshop on Waste-to-Energy Conversion Systems for Military Base Utilization*, P. Beltz and J. Frankosky, eds. (Battelle Columbus Laboratories, 1974), p C-23.

[6] G. W. Schanche, L. Greep, and B. Donahue, *Installation Solid Waste Survey Guidelines*, Technical Report E-75/ADA018879 (U.S. Army Construction Engineering Research Laboratory [CERL], 1975).

[7] *Facilities Engineering: Annual Summary of Operations for FY 75* (Office of the Chief of Engineers, 1976).



FOR ILLUSTRATION ONLY; COMPUTED FROM CUBIC YARDAGE DATA USING LOOSE BULK DENSITY OF 100 LB /CUBIC YARD.

Figure 1. Installation solid waste generation rates.

thrust of research and development in the waste-to-energy field in the past few years has been toward municipal-scale processes. Project development for smaller scale applications often requires dealing with unknown factors in scaling down municipal-scale equipment, selecting equipment which has been designed to process material other than relatively small masses of solid waste, and incorporating newly developed small-scale hardware which has no operational history to guarantee satisfactory performance.

Typology

Accurate identification of the constituency of an installation's solid waste stream is best accomplished by manually sorting numerous sampled loads into their major constituents and weighing each load. This method is described elsewhere and will not be detailed here.[4]

Table 1 shows a typical sample characterization of mixed solid waste from an Army installation. Encountering relatively large fractions of combustible materials such as mixed paper, cardboard, and wood, and smaller quantities of leather, rubber, and textiles is normal. Often these materials are found in a highly soiled condition, as shown in Table 2. Good system design depends on both accurate identification of waste stream components and the condition of the materials. Conventional waste characterization practice and current recycle guidelines make little note of the fact that the generally poor condition of typical Army waste materials considerably reduces their recycle potential, either as energy or materials.

In some potential resource recovery applications, the density of mixed solid waste is of interest. Installations commonly maintain solid waste management operation records on a volumetric basis. Quantities are normally reported in cubic yards; when mass data are required, an overall constant density is assumed for conversion. Numerous detailed investigations have clearly shown that the loose bulk density of typical military mixed solid waste is highly variable. In one instance, a solid waste survey reported densities ranging from 57 to 372 lb/cu yd (34 to 220 kg/m^3).[5] An average den-

---

[4] G. W. Schanche, L. Greep, and B. Donahue, *Installation Solid Waste Survey Guidelines*, Technical Report E-75/ADA018879 CERL, 1975).

[5] S. A. Hathaway, A. N. Collishaw, and J. P. Woodyard, *Technical Evaluation Study: Energy Recovery Incineration of Solid Waste at Naval Weapons Support Center, Crane, IN*, Technical Report E-97 (CERL, 1977).

Table 1

Typical Waste Characterization From an Army Installation: Sample 1

Constituent	Percent by Weight	Generation Rate Tons/Year* (MT/Year)
Mixed Waste Stream		
Paper, corrugated board	48	3245 (2943)
Wood	14	946 (858)
Misc. (inerts, sweepings, etc.)	10	676 (613)
Textiles	4	270 (245)
Plastics	4	270 (245)
Leather	1.5	102 (93)
Rubber	1.5	102 (93)
Food wastes	12	812 (736)
Yards and grounds waste	2	134 (121)
Metals	3	203 (184)
Total	100	6760 (6131)
Homogeneous Waste Stream		
Corrugated board		260 (236)
Mixed office paper stock		142 (129)
ADP cards		304 (276)
Waste motor pool oil		60,120 (2186 m^3) gal

*Based on 7-day weigh survey.

Table 2

Description of Waste Constituents in Table 1

Constituent	Description
Mixed Waste Stream	
Paper, corrugated board	Various types, some with fillers, mixed office waste; wet, dirty. Some ADP paper. Packaging.
Wood	Packaging, furniture, doors, desks, window frames, pallets, skids, toys, carpentry scraps, demolition and construction debris, dunnage; painted or stained, nails and bolts present, poor physical condition.
Misc.	Glass (primarily bottles of all colors), inorganic ash, stones, dust and dirt, unidentifiable refuse, plaster, misc. appliances, roofing materials, insulation.
Textiles	Cellulosic, protein, woven synthetics, rags, rugs, bedding materials; soiled and dirty.
Plastics	Film and rigid, polyvinyl chloride, polyethylene, styrene in packaging, housewares, furniture, toys, and nonwoven synthetics.
Leather, rubber	Shoes, tires, toys.
Food wastes	Wet garbage, unidentifiable mixture.
Yards and grounds wastes	Twigs and green branches, grass and leaves, logs, stumps.
Metals	Cans, wire, cable, foil, pipes, bicycle frames, strollers, eating utensils, carpentry shop waste, bedsprings, rusted sheet, demolition debris, shock absorbers, paint and oil cans, aerosol cans.
Homogeneous Waste Stream	
Corrugated board	Clean packaging from commissary, PX, warehouses, some staples, twine, metal stripping.
Mixed office paper stock	Ledger paper, ADP paper.
ADP cards	Clean, from ADP center.
Motor pool oil	Dirty sludge, contaminated with varnish, chlorinated solvents, misc. degreasing and unidentifiable chemical compounds.

sity of 147 lb/cu yd (87 kg/m^3) was computed, with a standard deviation of 70 lb/cu yd (42 kg/m^3).

Volumetric waste data reflect actual quantities of waste handled at an installation substantially less precisely than do mass or weight data. While volumetric data bear strongly on determining landfill life, directly measured weight data are of critical importance in determining the heating value of a waste stream, which is reported as Btu/pound. The use of "rule-of-thumb" density values in energy-recovery studies in which the raw data used are volumetric can often result in erroneous conclusions about the potential of an energy-recovery program.

Spatial Variability of Characteristics

The fact that the nature of Army solid waste differs from place to place reduces the credibility of generalizations about recycle potential. The generation rate is strongly tied to numerous phenomena such as the nature of the installation's mission, level of installation activity, climate, location, and local habits. An Army depot may generate up to 10 tons/

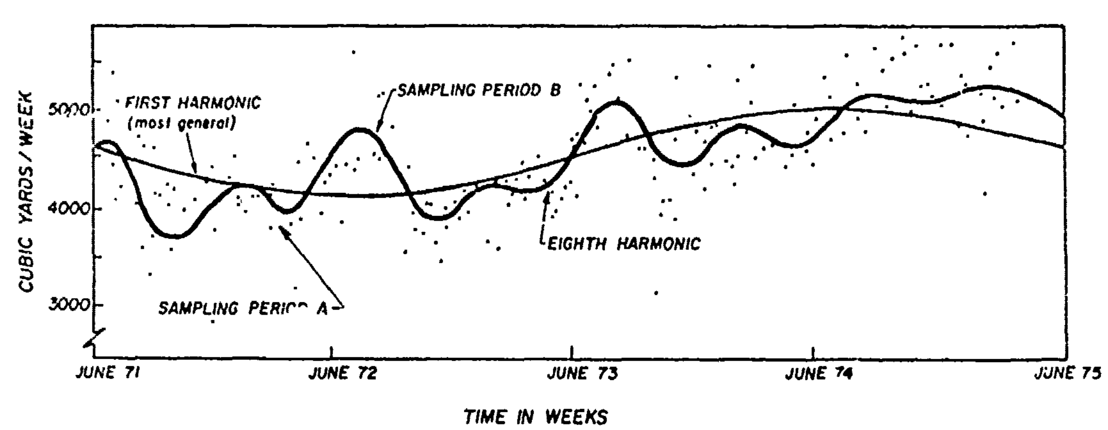


Figure 2. Time-distributed nature of military installation solid waste generation rate. From J. P. Woodyard, *The Prediction of Solid Waste Generation: A Review*, Masters Thesis (Department of Mechanical Engineering, University of Illinois, 1976), p 68.

day (9 MT/day) rubber waste, with nearly as high quantities of paper, cardboard, and wood,[10] while a typical Army installation with a total solid waste generation rate three times greater may not generate as much of those materials.[11] Detailed study may reveal that a site with a substantially smaller generation rate has far greater potential for resource recovery than one with a larger generation rate simply because the makeup of the waste is different.

Temporal Variability of Characteristics

The main solid waste characteristics revealed through a cursory survey at an installation usually exhibit a high degree of variability over time. Figure 2 shows weekly cubic yardage data for 4 calendar years at a military installation in CONUS. A detailed time series analysis was performed on these data to identify trends, which are represented by curves superimposed on the data points in Figure 2. Subsequent statistical analyses showed that the data exhibited both random and nonrandom components. The latter components were pronounced annual and seasonal periodicities. Superimposed on these gross trends was a lesser scale of minor randomness in the generation rate. The analysis clearly demonstrated that a waste survey at period A on the figure would have resulted in dramatically different conclusions about the generation rate than a survey at period B.

Similar analyses were performed on data from an Army depot (Figure 3). Here, long-term mass data on three major waste components were maintained. The dynamic, time-distributed nature of waste characteristics is again very clear. A survey made during weeks 31 through 33 would have led to far different conclusions about the potential of energy recovery than a survey made during weeks 23 through 25.

Comparing Tables 1 and 3 shows the dynamic nature of solid waste characteristics. The data in each table were recorded at the same location using the same methods, but were taken 90 days apart. Each table represents survey data consolidated for 1 day during which at least 10 randomly selected truckloads were sorted and weighed by constituent. The total generation rate in sample 2 (Table 3) is 46 percent greater than for sample 1 (Table 1). A generation rate of 26 TPD_s (24 MTPD_s) or 38 TPD_s (34 MTPD_s) could be assigned to the installation, depending on which sample is considered representative.

Impact of Variability on Design Point Determination of Energy-Recovery Systems

Equipment selection and concept design of combustion-based energy-recovery systems are based on essential properties of the waste as properly determined largely through laboratory analysis. The

---

[10] H. G. Rigo, D. N. Nelson, and M. E. Elbe, *Technical Evaluation Study: Solid Waste Generation and Disposal at Red River Army Depot, Texarkana, TX*, Technical Report E-33/AD779509 (CERL, 1974).

[11] S. A. Hathaway and J. P. Woodyard, *Technical Evaluation Study: Solid Waste as a Fuel at Fort Bragg, NC*, Technical Report E-95/ADA034416 (CERL, 1976).

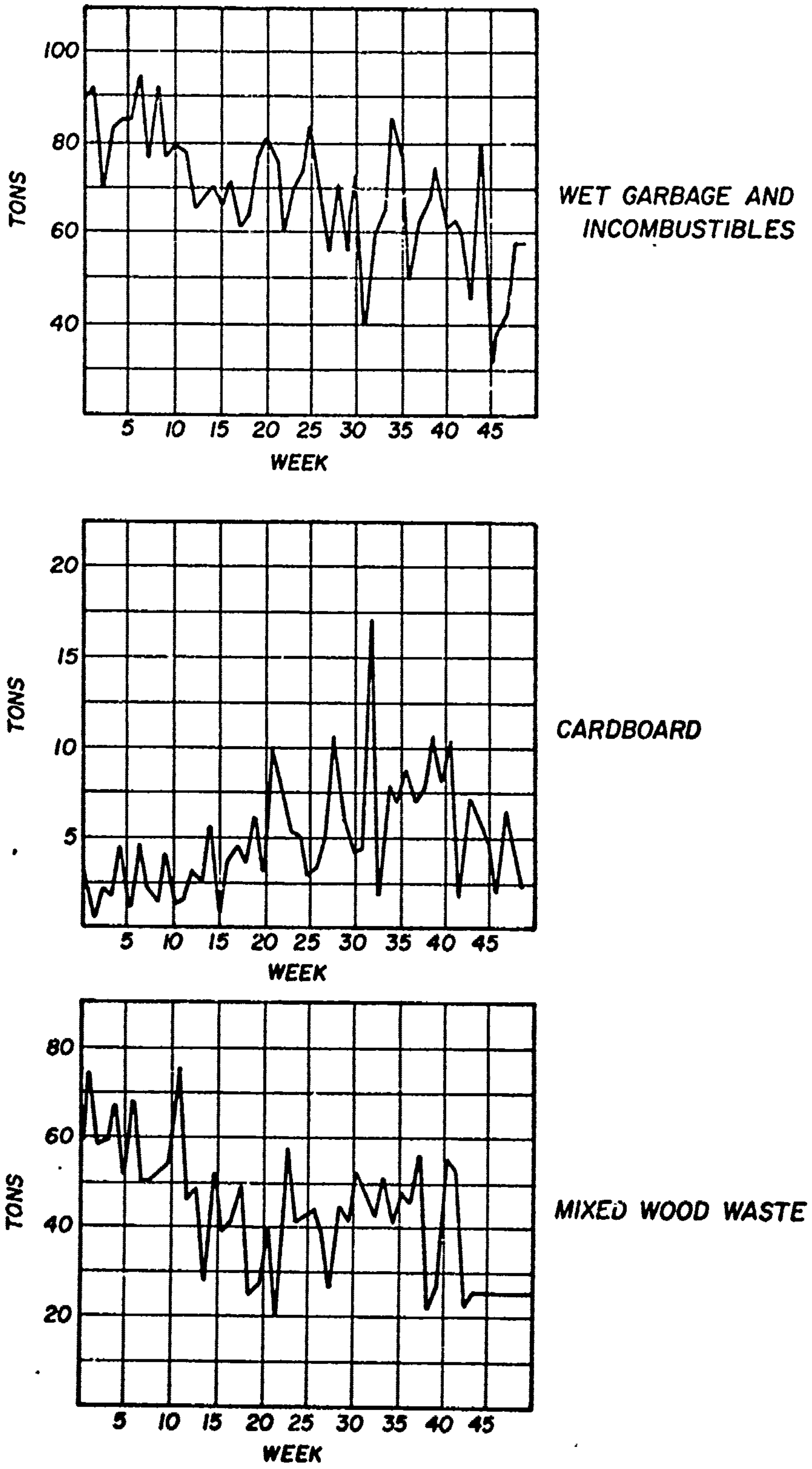


Figure 3. Time-distributed nature of composition of Army installation solid waste.

Table 3

Typical Waste Characterization From an Army Installation: Sample 2

Constituent	Percent by Weight	Generation Rate Tons/Year* (MT/Year)
Mixed Waste Stream		
Paper, corrugated board	49	4841 (4391)
Wood	5	494 (448)
Misc. (inerts, sweepings, etc.)	8	790 (717)
Textiles	2	198 (179)
Plastics	2	198 (179)
Leather	—	— —
Rubber	—	— —
Food wastes	20	1976 (1792)
Yards and grounds waste	12	1186 (1076)
Metals	2	197 (179)
Total	100	9880 (8961)
Homogeneous Waste Stream (No change from Table 1)		

*Based on 7-day weigh survey.

Table 4

Computation of Fuel Properties of Wastes From Tables 1 and 3

Constituent	Percent by Weight	Moisture Content, Percent	Volatile Matter, Percent	Fixed Carbon, Percent	Ash, Percent	Lower Heating Value, Btu/lb (kJ/kg)
Table 1 Data						
Paper, corrugated	48	4.93	71.77	9.29	14.01	6,200 (14 421)
Wood	14	12.00	67.00	18.00	3.00	8,300 (19 305)
Misc.	10	25.00	54.00	1.00	20.00	6,000 (13 955)
Textiles	4	10.00	80.00	7.00	3.00	8,000 (18 607)
Plastics	4	1.00	95.00	2.50	1.50	14,600 (33 958)
Leather	1.5	4.31	62.08	8.12	25.45	9,071 (21 098)
Rubber	1.5	2.00	83.00	—	15.00	11,300 (26 283)
Food wastes	12	58.52	36.71	2.68	2.09	4,709 (10 953)
Yards/grounds waste	2	56.50	33.42	8.20	1.88	3,779 (8 790)
Metals	3	2.00	1.50	1.50	95.00	120 (279)
Composite	100.0	15.29	63.53	8.11	13.07	6,592 (15 332)
Table 3 Data						
Paper, corrugated	49	4.93	71.77	9.29	14.01	6,200 (14 421)
Wood	5	12.00	67.00	18.00	3.00	8,300 (19 305)
Misc.	8	25.00	54.00	1.00	20.00	6,000 (13 955)
Textiles	2	10.00	80.00	7.00	3.00	8,000 (18 607)
Plastics	2	1.00	95.00	2.50	1.50	14,600 (33 958)
Leather	—	4.31	62.08	8.12	25.45	9,071 (21 098)
Rubber	—	2.00	83.00	—	15.00	11,300 (26 283)
Food wastes	20	58.52	36.71	2.68	2.98	4,709 (10 953)
Yards/grounds waste	12	56.50	33.42	8.20	1.88	3,779 (8 790)
Metals	2	2.00	1.50	1.50	95.00	120 (279)
Composite	100.0	23.76	57.72	7.27	11.25	5,783 (13 451)

example shown in Table 4, in which only some of these properties are considered, is based on data from Tables 1 and 3. Sample 1 revealed a waste generation rate of 26 TPD_5 (24 MTPD_5). With a lower heating value of 6592 Btu/lb (15 332 kJ/kg), the daily quantity of waste energy available is 342.8 MBtu (362 GJ). Sample 2 had a lower heating value of 5783 Btu/lb (13 451 kJ/kg), more than 12 percent less than that of sample 1. However, due to its greater computed generation rate, sample 2 revealed a daily quantity of waste energy equal to 439.5 MBtu (463.7 GJ), or 28 percent more than sample 1.

In the study which produced these data, it was not known which sample to consider representative, or whether either sample accurately represented the situation on the installation. Table 5 shows the range of values obtained for proximate and ultimate analyses in that study. The impact of the differences on system hardware requirements and total economics was assessed. Data from sample 1 supported a design concept which included one package incinerator/heat-recovery boiler system operating 3 shifts/day, 5 days/week. Data from sample 2 supported a design concept which included two package incinerator heat-recovery boilers. While the first design concept included a special low-horsepower shredder for bulky combustibles, the second did not, because only a trivial amount of such material was observed during the second waste survey period. Capital required for the system demanded by sample 2 data amounted to $2.2 million. Capital required for the system demanded by sample 1 data totaled $1.4 million.

This dilemma catalyzed an accelerated effort aimed at developing a reliable methodology by which to survey installation solid waste to determine combustion system design points. Two major methodologies currently exist by which combustion system design points are established. The first was described in the **General** section of this chapter. The second merely adds 25 percent to the available tons/hour waste available to a system under a given operating schedule.[12] Neither method directly considers the time-variability of solid waste characteristics. Both methods assume that combustion hardware is designed on the basis of mass throughout (tons/hour) rather than heat release rate. Neither method recommends how to accurately characterize an installation's solid waste for either project development or design purposes.

Table 5

Variability of Chemical Composition of Installation Solid Waste

Proximate Analysis	**Mass Percent**
Moisture	14.70 - 32.50
Ash	9.25 - 30.63
Volatiles	25.04 - 64.55
Fixed carbon	0.59 - 14.90
Lower heating value	3900 - 6970 Btu/lb (9 071 - 16 211 kJ/kg)
Ultimate Analysis	
Moisture	12.72 - 32.50
Carbon	22.40 - 34.04
Hydrogen	3.70 - 4.86
Nitrogen	0.20 - 0.40
Chloride	0.11 - 0.46
Sulfur	0.18 - 0.51
Ash	9.25 - 30.63
Oxygen	14.68 - 33.10
Mineral Analyses	
Silica	47.60 - 61.28
Alumina	5.10 - 12.44
Titania	0.80 - 1.45
Magnesia	1.02 - 1.60
Lime	6.29 - 19.00
Phosphorus pentoxide	0.95 - 5.20
Ferric oxide	3.44 - 4.87
Sulfur trioxide	1.75 - 14.66
Potassium oxide	1.50 - 3.01
Sodium oxide	4.44 - 6.30
Undetermined	0.05 - 0.80

3 BASIC CONVERSION PROCESSES

General

Most current and emerging energy-recovery systems are based on conversion of mixed solid waste to a refined solid, liquid, or gaseous fuel. All energy-recovery processes take advantage of the chief physical and chemical properties of the waste material and, most important, its organic constituency. The two processes for energy-recovery utilization of solid waste which are currently most highly developed are combustion and pyrolysis. This chapter provides a very general background to the more detailed treatment of particular conversion systems in the ensuing chapters. The definition and main properties of solid, liquid, and gaseous fuels are described, as are the processes of combustion and pyrolysis.

---

[12] *Design Manual-Mechanical Engineering* (Naval Facilities Engineering Command, 1972), p 3-2-5.

Properties of Fuel[13]

General

Mixed solid waste can be used in energy-recovery systems either in unprocessed condition or after refinement into a fuel. Numerous systems in both the developmental and commercial stages use mixed solid waste as a solid fuel. Other systems use processes by which mixed solid waste is converted to a low-grade combustible gas or fuel oil.

Solid Fuels

Solid fuels are composed of carbon and hydrogen with various amounts of nitrogen, oxygen, and mineral matter included. The chemical constituents of solid fuels are determined by ultimate and proximate analyses.

Ultimate analysis of a solid fuel is a precise chemical determination in which six basic fuel components (carbon, hydrogen, oxygen, nitrogen, sulfur, and ash) are listed in percent by weight. When used with the higher (ash- and moisture-free basis) and lower (as-fired) heating values of the solid fuel, the ultimate analysis provides the data required to complete combustion calculations and to predict some aspects of the fuel's behavior in a furnace.

Proximate analysis provides additional data by which to predict fuel combustion performance. This analysis reveals the fuel's content of volatile matter, ash, fixed carbon, and moisture. Volatile matter is combustible or incombustible gaseous and vaporous products which can be expelled by heating the fuel. It consists of hydrocarbons and other gases resulting from distillation and decomposition, and reveals the gaseous character of the fuel as a very general indication of fuel reactivity under high temperatures. Ash, sometimes referred to as "inerts," is simply incombustible solid matter. Fixed carbon is solid carbonaceous residue in the fuel after ash and volatiles have been removed. It does not represent all the carbon in the solid fuel, as listed in the ultimate analysis, because the volatile matter contains considerable carbon in the form of complex hydrocarbon compounds. The fixed carbon generally represents that portion of the fuel which must be burned in solid state, either in the fuel bed on a stoker or as pulverized solid particles in suspension firing. Moisture as determined for the proximate analyses consists only of the free or surface moisture present with the solid fuel. Additional hydrogen and oxygen may be in the fuel after the free moisture is driven off, but they normally are not united to form water.

The heating value of a solid fuel is expressed as Btu/pound of fuel on an as-received, dry, or moisture- and ash-free basis. The higher heating value of a solid fuel includes the latent heat of water vapor in the products of combustion. In actual practice, water vapor in the waste gas is not cooled below its dewpoint, and this heat is not available for making steam. The latent heat of vaporization is subtracted from the higher heating value to give a net (lower) heating value.

The ultimate and proximate analyses and heating values of a solid fuel are only part of the information required for design of heat-recovery systems. Ignition rate and ash characteristics are also required. To obtain a clear picture of the ignition rate, a fuel burning profile is established. The profile shows the rate of reaction (or time required for volatilization) and is usually expressed as the rate of fuel weight loss as a function of furnace temperature.

Ash characteristics are also critical. The ash sintering strength (comparative compressive strength of sintered ash) must be established to obtain an idea of its erosiveness. The ash viscosity-temperature relationship must also be known, since "plastic" ash had adherent properties which cause problems in furnaces. A spectrographic analysis of ash is required to reveal its basic elemental composition. Ash fusion temperatures are determined and reported in terms of initial deformation, softening, and fluid temperatures. Table 6 shows the major properties of solid fuels (including those derived from solid waste).

Liquid and Gaseous Fuels

In some emerging waste-to-energy systems, mixed solid waste is converted into a low-grade fuel oil or gas which can then be burned in an energy-recovery system. Fuel oils produced in this way are composed of a large number of hydrocarbon compounds, each of which has individual properties and characteristics. It is common practice to classify the many hydrocarbons present into five chemical

---

[13] M. Smith and K. Stinson, *Fuel and Combustion* (McGraw-Hill, 1952); and G. Fryling, ed., *Combustion Engineering* (Combustion Engineering, Inc., 1966).

Table 6

Analysis of Solid Fuels

Fuel	Proximate Analysis, Percent				Ultimate Analysis, Percent						Heating Value, Btu/lb	
	Moisture	Volatiles	Fixed Carbon	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	As-Reported	Dry Basis
Peat	56.8	26.0	11.2	6.0	23.1	9.6	59.6	1.3	0.4	6.0	3,600	8,330
Lignite	34.8	28.0	30.8	6.2	42.4	6.7	43.3	0.7	0.7	6.2	7,210	11,060
Bituminous Coal												
Low VM, PA	8.3	20.5	70.0	6.2	80.7	4.7	5.3	1.1	1.8	6.2	14,310	14,800
Low VM, AR	3.4	16.2	71.8	8.6	79.6	4.3	4.8	1.7	1.0	8.6	13,700	14,190
Med VM, VA	3.1	21.8	67.9	7.2	80.1	5.0	5.2	1.5	1.0	7.2	14,030	14,480
Med VM, AL	2.8	23.8	62.4	11.0	76.9	4.8	5.1	1.5	0.7	11.0	13,450	14,870
High VM, KY	3.1	35.0	58.9	3.0	79.2	5.7	10.0	1.5	0.6	3.0	14,270	14,750
High VM, OH	8.2	36.1	48.7	7.0	68.4	5.6	16.4	1.4	1.2	7.0	13,160	13,250
High VM, IL	12.1	40.2	39.1	8.6	62.8	5.9	17.4	1.0	4.3	8.6	11,480	13,050
Subbituminous, OH	19.6	30.5	45.9	4.0	58.8	6.0	29.6	1.8	0.3	4.0	10,130	12,600
Anthracite Coal, PA	2.3	3.1	87.7	6.9	86.7	2.2	2.9	0.8	0.5	6.9	13,540	13,860
Emianthracite, PA	3.0	8.4	78.9	9.7	80.2	3.6	4.7	1.1	0.7	9.7	13,450	13,870
Emianthracite, VA	3.1	10.6	66.7	19.6	70.5	3.5	5.0	0.8	0.6	19.6	11,850	12,230
Refuse-Derived Fuels*												
Coarse RDF, NJ	26.6	30.3	28.3	14.8	42.3	5.9	33.4	3.2	0.4	14.8	4,250	6,500
Fluff RDF, ME	26.0	46.0	4.0	25.0	35.4	5.7	30.5	3.3	0.1	25.0	3,757	6,400
Fluff RDF, CA	18.0	60.0	7.0	15.0	37.5	6.1	38.7	2.6	0.1	15.0	5,633	7,250
Fluff RDF, CA	16.2	34.5	27.4	21.9	39.6	5.3	32.8	0.9	—	21.9	5,700	7,100
Dust RDF, NY	5.0	72.7	17.3	5.0	48.4	6.3	38.6	1.5	0.2	5.0	7,360	8,000

*Average data which may not be chemically precise.

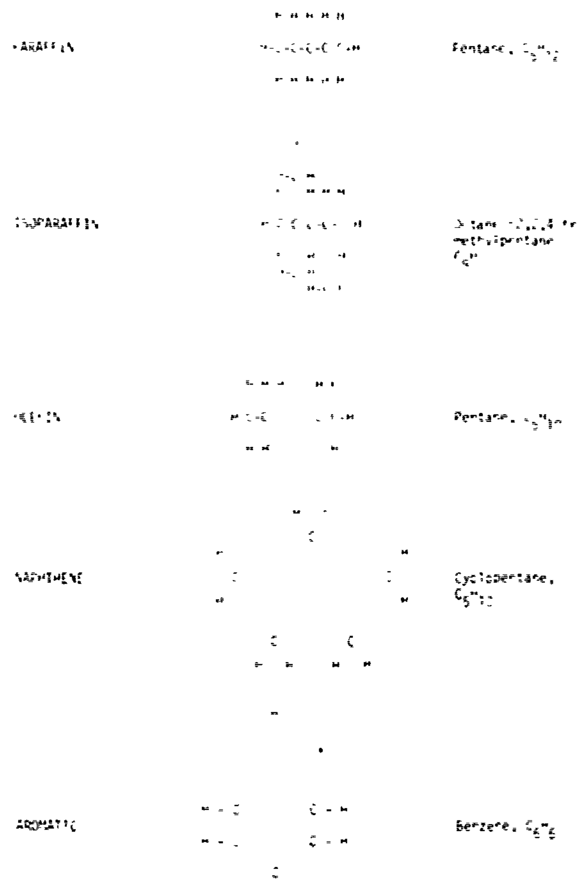


Figure 4. Molecular structures of fuel oils.

groups characterized by the quantitative relation of carbon and hydrogen atoms and the molecular structure (Figure 4). Paraffins are straight chains having the general chemical formula C_nH_{2n+2}, where n is the number of atoms. An example of a paraffin is methane (CH_4). Isoparaffins have four or more carbon atoms and may possess the same number of carbon and hydrogen atoms as a normal paraffin, but have them arranged in a different manner. Octane, a paraffin, has the formula C_8H_{20}. Isooctane, an isomer of paraffin (isoparaffin), has the same number of hydrogen and carbon atoms, but has three methyl (CH_3) groups attached to a pentane (C_5H_{12}) chain. The name of the isomer is 2,2,4-trimethylpentane, with the numbers indicating the positions (from the left) of the methyl groups. Olefins are unsaturated compounds; the maximum amount of hydrogen atoms is not present, which causes some carbon atoms to share two or more valence bonds. The general formula for this group is C_nH_{2n}. Naphthenes are saturated, stable compounds with a ring structure having the general formula C_nH_{2n}. Aromatics are unsaturated but stable ring compounds having the general chemical formula C_nH_{2n-6}.

Molecular structure can have a variety of configurations, particularly for larger, heavier molecules. Each isomer, for example, may differ only slightly from others in physical and chemical characteristics (e.g., boiling point, specific gravity, conductivity), but the combustion characteristics may vary widely. Isooctane burns very smoothly in gasoline engines. In contrast, normal octane (the paraffin C_8H_{12}) is a poor engine fuel. Unsaturated compounds such as olefins and a subgroup, the diolefins (C_nH_{2n-2}), possess generally good combustion characteristics. Diolefins, however, are thought to be the cause of gum formation in gasoline The physical properties of naphthenes are similar to those of normal paraffins, but their combustion properties are more like those of isoparaffins. Aromatics have good combustion characteristics in engines; unlike the olefins, there is no tendency for oxygen atoms to be picked up and take the place of the double bond.

Crude oils drawn from the earth commonly are refined into different products. Refining is a fractional distillation process by which crude oil, which usually consists of an indeterminate mix of different hydrocarbon compounds, is separated into different fractions which are then individually further treated and processed into final products such as gasoline, various grades of fuel oil, etc. An implicit objective of the liquid fuel production process is to yield a final product whose chemical composition is determinable and reasonably constant over time. The known chemical and combustion properties of a judiciously manufactured liquid fuel contribute to the optimal design of fuel-burning equipment. If the chemical composition of a liquid fuel is not known with an adequate degree of precision, a degree of risk is involved in any design effort. A similar risk is introduced when the chemical composition of a fuel varies over a wide range. Combustion calculations for liquid fuels are based on the weight percentage of carbon and hydrogen, the weight ratio of hydrogen to carbon, and the ratio of the number of hydrogen atoms to the number of carbon atoms in the fuel.

Gaseous fuels are difficult to store in large volumes, but are advantageous in that they are generally cleaner than their solid and liquid counterparts. Gas flame control is relatively easy, and complete combustion with no smoke can usually be easily achieved. Natural gas consists chiefly of methane (CH_4, a paraffin), with varying quantities of heavier hydrocarbons. Gaseous fuels can be produced from numerous parent materials, some of which are shown in Table 7 along with the salient chemical characteristics of the respective fuels.

The process most often used to convert mixed solid waste to a low-grade fuel oil or gas is pyrolysis, which is described in the next section.

Basic Elements of Pyrolysis

General

Pyrolysis is destructive distillation. It is a process in which organic matter is thermally decomposed in either an oxygen-free or low-oxygen atmosphere. The chief useful product of pyrolysis is a comparatively energy-rich gas or oil which can be either directly fired for heat recovery on site or transported to users by conventional modes. Unlike incineration, which is an exothermic combustion reaction with air, pyrolysis is endothermic, requiring application of heat either indirectly or by partial oxidation (or other reactions) occurring in the pyrolysis reactor. While the products of incineration are chiefly carbon dioxide and water, the products of pyrolysis are usually a highly complex mixture of primarily combustible gases, liquids, and solid residues, which are of potential use as fuels and chemical raw materials.

The chief advantages of pyrolysis are related to changes in the point of material volatilization in the energy-recovery process. In incineration, fuel volatilization and oxidation are an integrated operation. Pyrolysis of waste to a fuel removes the point of volatilization from the oxidation heat exchange process. Hence, there is better control of the full combustion process, an essentially cleaner and more predictable fuel, and often easier management of ash and residue. In addition, less excess air is required to combust pyrolytic fuel than mixed solid waste. Therefore, off-gas volumes and particulate loadings are less in a pyrolysis system than in pure incineration, making the economies of system maintenance and air pollution control relatively more attractive.

Basic Pyrolysis Chemistry[14]

Carbon, hydrogen, and oxygen are the principal constituents of the organic portion of Army mixed solid waste. Comparatively minor quantities of chlorine, sulfur, nitrogen, and numerous other elements are also present. In treating the reaction chemistry of municipal mixed solid waste, it is common practice to assume that the ratios of the major elements approximate those in cellulose and to represent the waste chemically as $(C_6\ H_{10}\ O_5)_n$, where n represents a variable number of the basic chemical units. For engineering purposes, the same assumption can be used in considering Army mixed solid waste. For simplicity in illustration, the nature chain polymeric of cellulose can be ignored, and the chemical expression $C_6H_{10}O_5$ used.

A simple pyrolysis reaction is illustrated by carbon reacting with water and carbon dioxide to form carbon monoxide through application of heat ($\triangle$):

$$C + H_2O + \triangle \rightarrow H_2 + CO \qquad \text{[Eq 1]}$$

$$C + CO_2 + \triangle \rightarrow 2CO \qquad \text{[Eq 2]}$$

In actuality, cellulose breaks down into new organic compounds which have less complex molecular structures than the parent cellulose. A typical reaction equation for the pyrolysis of cellulose cannot be written; factors such as temperature, time, pressure, and the presence of catalysts control the precise products which are formed. A general conceptual expression for the pyrolysis of cellulose is:

$$C_6H_{10}O_5 \rightarrow W + X + Y + Z \qquad \text{[Eq 3]}$$

where W = fuel gas (including carbon dioxide and water)
X = pyrolytic oil,
Y = other condensibles (oxygenated organics in water),
Z = carbonaceous solid residue (char).

The reaction shown in Eq 3 contrasts with normal combustion (incineration) of cellulose, in which suf-

---

[14] N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

Table 7

Characteristics of Gaseous Fuels*

Family	Name	Formula	Molecular weight	API gravity, 60 F	Specific gravity, 60/60 F	Freezing point, F[b]	Boiling point, F[c]	h, evapo- Btu/lb[d]	% by weight Carbon	% by weight Hydrogen	H/C ratio, by atoms	Theor. lb air/lb fuel
n-Paraffins and iso-paraffins	Methane	CH_4	16.04	—	—	−296.5	−258.7	—	75.0	25.0	4.00	17.2
	Ethane	C_2H_6	30.07	—	-	−297.8	−127.5	—	80.0	20.0	3.00	16.0
	Propane	C_3H_8	44.09	147.0	0.508	305.8	− 43.7	147.1	81.8	18.2	2.66	15.6
	n-Butane	C_4H_{10}	58.12	110.8	0.584	−217.0	+ 31.1	155.8	82.8	17.2	2.50	15.4
	Isobutane	C_4H_{10}	58.12	119.8	0.563	255.3	10.9	141.4	82.8	17.2	2.50	15.4
	n-Pentane	C_5H_{12}	72.15	92.7	0.631	201.5	96.9	157.5	83.3	16.7	2.40	15.3
	2-Methylbutane	C_5H_{12}	72.15	94.9	0.625	255.8	82.1	146.6	83.3	16.7	2.40	15.3
	n-Hexane	C_6H_{14}	86.17	81.6	0.664	139.6	155.7	157.4	83.7	16.3	2.34	15.2
	2,2 Dimethylbutane	C_6H_{14}	86.17	84.9	0.654	147.5	121.5	138.2	83.7	16.3	2.34	15.2
	n-Heptane	C_7H_{16}	100.20	74.2	0.688	−131.1	209.2	156.8	84.0	16.0	2.29	15.1
	2,2,3-Trimethylbutane	C_7H_{16}	100.20	72.4	0.694	− 12.9	177.6	137.5	84.0	16.0	2.29	15.1
	n Octane	C_8H_{18}	114.22	68.6	0.707	− 70.2	258.2	156.1	84.2	15.8	2.25	15.1
	4-Methylheptane	C_8H_{18}	114.22	68.1	0.709	−185.7	243.9	149.3	84.2	15.8	2.25	15.1
	2,2,4 Trimethylpentane	C_8H_{18}	114.22	71.8	0.696	−161.3	210.6	132.2	84.2	15.8	2.25	15.1
	n Nonane	C_9H_{20}	128.25	64.5	0.722	− 64.5	303.4	155	84.4	15.6	2.22	15.0
	2,2,4,4-Tetramethylpentane	C_9H_{20}	128.25	63.9	0.724	− 87.8	252.1	127.8	84.4	15.6	2.22	15.0
	n-Decane	$C_{10}H_{22}$	142.28	62.3	0.730	− 22	345	155	84.5	15.5	2.20	15.0
	n-Tetradecane	$C_{14}H_{30}$	198.38	54.0	0.763	+ 42	484	154	84.9	15.1	2.14	14.9
	n Hexadecane	$C_{16}H_{34}$	226.43	51.5	0.774	65	536	154	85.0	15.0	2.12	14.9
	n-Pentatriacontane	$C_{35}H_{72}$	492.93	49.5	0.781	176	628	—	85.3	14.7	2.06	14.8
Olefins	Ethylene	C_2H_4	28.05	—	—	−272.5	−154.7	—	85.7	14.3	2.00	14.7
	Propylene	C_3H_6	42.08	139.6	0.522	−301.5	− 53.9	—	85.7	14.3	2.00	14.7
	Isobutene	C_4H_8	56.10	104.3	0.600	−220.6	+ 19.6	157.7	85.7	14.3	2.00	14.7
	Pentene	C_5H_{10}	70.13	87.5	0.646	−265.4	86.0	—	85.7	14.3	2.00	14.7
	Hexene	C_6H_{12}	84.16	77.2	0.678	−218	146.4	—	85.7	14.3	2.00	14.7
	Octene	C_8H_{16}	112.21	65.0	0.720	−152.3	250.3	156.0	85.7	14.3	2.00	14.7
	Hexadecene	$C_{16}H_{32}$	224.42	49.2	0.783	+ 39	527	—	85.7	14.3	2.00	14.7
Naphthenes	Cyclopentane	C_5H_{10}	70.13	57.2	0.750	−136.8	120.7	174.7	85.7	14.3	2.00	14.7
	Cyclohexane	C_6H_{12}	84.16	49.2	0.783	+ 43.8	177.3	168.8	85.7	14.3	2.00	14.7
	Ethylcyclohexane	C_8H_{16}	112.21	47.1	0.792	−168.3	269.2	155.1	85.7	14.3	2.00	14.7
Aromatics	Benzene	C_6H_6	78.11	28.4	0.885	+ 42.0	176.2	186.3	92.3	7.7	1.00	13.2
	Toluene	C_7H_8	92.13	30.8	0.872	−139.0	231.1	177.3	91.3	8.7	1.14	13.5
	o-Xylene	C_8H_{10}	106.16	28.4	0.885	− 13.3	292.0	175.9	90.6	9.4	1.25	13.7
Alcohols	Methyl	CH_3OH	32.0	47.2	0.792	−144	149	502	37.5	12.5	—	6.4
	Ethyl	C_2H_5OH	46.0	48.8	0.785	−179	172	396	52.2	13.0	—	9.0
	Propyl	C_3H_7OH	60.0	45.6	0.799	—	208	295	60.0	13.3	—	10.5
	Butyl	C_4H_9OH	74.1	44.2	0.805	+ 26	244	254	65.0	13.5	—	11.1
Acetylene	Acetylene	C_2H_2	26.04	—	—	−114	−114	—	92.3	7.7	1.00	13.3

*From M. Smith and K. Stinson, *Fuels and Combustion* (McGraw-Hill, 1952).

[b] In air, 1 atm.

[c] At 1 atm.

[d] Latent heat of fuel at constant pressure, 77°F.

SI conversion factors (°F − 32)5/9 = °C; 1 Btu/lb = 2.326 kJ/kg; 1 lb = 0.4535 kg

ficient oxygen is supplied to allow for complete oxidation of the material and heat is liberated. Solid residues are always present as a pyrolysis product, while the relative quantities of gaseous and liquid products depend essentially on the temperatures involved.

Product yields can be controlled by applying catalysts or high pressure, by the use of oxidizing reactants such as air, oxygen, or water, or by the use of reducing reactants such as carbon monoxide or hydrogen. Obtaining the following types of reactions is possible:*

$$C_6H_{10}O_5 + 1/2\,O_2 \rightarrow 6CO + 5H_2 \text{ (partial oxidation)} \quad \text{[Eq 5]}$$

$$C_6H_{10}O_5 + H_2O + \Delta \rightarrow 6CO + 6H_2 \text{ (reforming)} \quad \text{[Eq 6]}$$

$$C_6H_{10}O_5 + H_2 + \text{Pressure} \rightarrow \text{Oil} + H_2O \text{ (hydrogenation)} \quad \text{[Eq 7]}$$

$$C_6H_{10}O_5 + 12H_2 + \text{Pressure} \rightarrow 6CH_4 + 5H_2O \text{ (hydrogasification)} \quad \text{[Eq 8]}$$

---

*In pyrolysis systems approaching commercialization, only simple pyrolysis (Eq 3) and partial oxidation (Eq 5) are used.

$$C_6H_{10}O_5 + CO + H_2O + \text{Pressure} \rightarrow \text{pyrolytic oil}$$

$$\text{(hydrooxynation)} \qquad \text{[Eq 9]}$$

Fuel gas is the primary product from processes in which partial oxidation and reforming reactions predominate; under low temperature conditions, considerable quantities of oxygenated liquids also result. Hydrogenation reactions may be employed in processes to produce either oil (300°-350°C, 200-300 atm) or principally methane gas (650°C, 80-200 atm). Pyrolytic oil is produced through hydro-oxynation under high pressure at 350°C. As a general rule, higher pyrolysis temperatures increase gaseous yields in simple pyrolysis. Gas-producing processes usually take place in the temperature range between 700° and 1000°C, while processes yielding high quantities of pyrolytic oil usually take place at about 500°C.

Fuel gas composition is highly dependent upon pyrolysis conditions. In partial oxidation reactions in which air is introduced, the fuel gas is diluted with nitrogen, limiting its use to equipment designed for low volumetric heating fuel gases. Hydrogenation processes in which methane (CH_4) is the principal product may yield higher heating value gases, depending mainly on the presence of unreacted hydrogen, which has a lower volumetric heating value than methane. Pyrolytic gases containing mixtures of hydrogen and carbon monoxide can be converted to natural gas substitutes.

Composition of Pyrolysis Fuels[15]

Table 8 shows the results of simple pyrolysis of a sample dried, shredded municipal mixed solid waste with most inorganics removed. Pyrolysis took place at 500°C and atmospheric pressure. The advantage of removal of inorganics is clearly reflected in the ash content of the char, which would have been substantially higher without preprocessing. If the waste had not been dried prior to simple pyrolysis, the water mass fraction (in substance attributed to condensation) would have been larger. Increased feed moisture both dilutes soluble organics, causing difficulty in their recovery and disposal, and increases the amount of heat which must be added to the pyrolysis reactor.

As noted earlier, the quantity, nature, and composition of the pyrolysis product is determined by several variables. Table 9 indicates the effect of temperature on pyrolysis yields. As simple pyrolysis temperatures rise, the mass percent of product accounted for by gases increases. Table 10 illustrates the effect of pyrolysis temperatures on gas composition; the hydrogen content of the gases increases with temperature. As shown in Table 11, however, liquid composition does not change dramatically with temperature. As expected, char

Table 8

Example Simple Pyrolysis Product Composition*

Fraction	Char	Pyrolytic Oil		Gas	Water
Mass yield, (%)	20	40		27	13
	Mass, %	Mass, %		Volume, %	Contains
Carbon	48.8	37.5	Water	0.1	Acetaldehyde
Hydrogen	3.9	7.6	Carbon Monoxide	42.0	Acetone
Nitrogen	1.1	0.9	Carbon Dioxide	27.0	Formic Acid
Sulfur	0.3	0.1	Hydrogen	10.5	Furfural
Ash	31.8	0.2	Methyl Chloride	0.1	Methanol
Chlorine	0.2	0.3	Methane	5.9	Methyl Furfural
Oxygen (by diff.)	13.9	33.4	Ethane	4.5	Phenol
			Hydrocarbons C_3 to C_7	8.9	Etc.
			Higher Hydrocarbons	1.0	
Total	100.0	100.0		100.0	
Heating Value	9000 Btu/lb 5000 CAL/G	10,500 Btu/lb 5,830 CAL/G		550 Btu/F 5172 KCAL/NCM	

*From N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

---

[15] N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

analyses (Table 12) exhibit decreased volatile matter as temperature increases.

Basic Elements of Combustion

Since the final products in pyrolysis systems must go through a combustion process, the basic elements of combustion are important for both combustion and pyrolytic systems. Combustion is the rapid oxidation of fuel or, more simply, burning. In the simplest case, oxygen, supplied with nitrogen in combustion air, is combined with carbon and hydrogen in the fuel to form carbon dioxide and water. The reaction is exothermic, i.e., it releases heat. As in any reaction, the mass of the reactants equals the mass of the products.

The relative amounts of reactants used to obtain a particular product is always the same. Also, the

Table 9

Temperature Effects on Mass Yields From Simple Pyrolysis*

Pyrolysis Temperature, °C (°F)	482 (900)	649 (1200)	816 (1500)	927 (1700)
Product Yields, weight percent				
Gases	12.33	18.64	23.69	24.36
Volatile condensables**	43.37	49.20	47.99	46.96
Other condensables	17.71	9.98	11.68	11.74
Char	24.71	21.80	17.24	17.67
	98.12	99.62	100.60	100.73

* From N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

**Portion of condensables which evaporate at 103°C, including water.

Table 10

Temperature Effects on Composition of Product Gas From Simple Pyrolysis*

Temperature, °C (°F)	482 (900)	649 (1200)	816 (1500)	927 (1700)
Gas Composition, volume percent				
Carbon Monoxide	33.50	30.49	34.12	35.25
Carbon Dioxide	44.77	31.78	20.59	18.31
Hydrogen	5.56	16.58	28.55	32.48
Methane	12.43	15.91	13.73	10.45
Ethane	3.03	3.06	0.77	1.07
Ethylene	0.45	2.18	2.24	2.43
	99.74	100.00	100.00	99.99
Heating Value,**				
cal/NCM 2930	2930	3780	3680	3610
(Btu/SCF)	(312)	(403)	(392)	(385)

*From N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

**Gross heating value by calculation.

Table 11

Temperature Effects on Composition of Organic Products From Simple Pyrolysis*

Pyrolysis Temperature, °C (°F)	649 (1200)	816 (1500)
Weight Percent of Condensable Organics		
Acetaldehyde	13.0	10.5
Acetone	18.0	16.5
Methylethylketone	4.3	4.9
Methanol	20.6	23.5
Chloroform	1.0	2.1
Toluene	1.3	3.2
Furfural	6.5	5.6
Acetic acid	2.6	2.5
Methylfurfural	7.2	8.0
Naphthalene	1.3	2.1
Methylnaphthalene	6.9	6.7
Phenol	1.6	1.8
Cresol	1.3	1.4
	100.0	100.0

*From N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

Table 12

Temperature Effects on Composition of Solid Residue From Simple Pyrolysis*

Pyrolysis Temperature, °C (°F)	482 (900)	649 (1200)	816 (1500)	927 (1700)
Solid Residue Composition, weight percent				
Volatile matter	21.81	15.05	8.13	8.30
Fixed carbon	70.48	70.67	79.05	77.23
Ash	7.71	14.28	12.82	14.47
	100.00	100.00	100.00	100.00
Gross Heating Value,				
cal/g	6730	6840	6400	6330
(Btu/lb)	(12,120)	(12,280)	(11,540)	(11,400)

*From N. Weinstein and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

heat liberated is proportional to the amount of reactants used. One carbon atom combines with one oxygen molecule to produce one carbon dioxide molecule and a given amount of heat ($\triangle$).

$$C + O_2 \rightarrow CO_2 + \triangle \qquad \text{[Eq 10]}$$

The reaction of hydrogen and oxygen to form water is much the same.

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \triangle \qquad \text{[Eq 11]}$$

In the absence of sufficient oxygen to burn carbon completely, carbon monoxide may be formed.

$$2C + O_2 \rightarrow 2CO + \triangle \qquad \text{[Eq 12]}$$

If additional oxygen is supplied after this reaction has occurred, the carbon monoxide may combine with oxygen to form carbon dioxide and liberate heat.

$$2CO + O_2 \rightarrow 2CO_2 + \triangle \qquad \text{[Eq 13]}$$

Under favorable conditions in a reducing atmosphere, the above reactions will occur in opposite directions and heat will be absorbed rather than released. The reaction is then said to be endothermic.

In combustion reactions, the fuel is usually not pure hydrogen or carbon but a combination of the two and other elements. As noted earlier, these compounds are hydrocarbons, which can be fairly simple, such as methane (CH_4), or complex. The oxygen used in these reactions is supplied in air, which is a mixture of oxygen and relatively inert nitrogen in a proportion of about 4:1 ($N_2:O_2$) on a volume basis. Air also contains traces of other elements, which for most purposes can be ignored in engineering computations. An example of a hydrocarbon burning in combustion air is the complete combustion of cellulose

$$C_6H_{10}O_5 + CO_2 + 24N_2$$

$$\rightarrow 6CO_2 + 5H_2O + 24N_2 + \triangle \qquad \text{[Eq 14]}$$

In the above reactions, the amount of oxygen or air supplied is exactly the amount necessary to completely burn the fuel. This is called "theoretical air." In most combustion, more than this amount of air is supplied in order to promote complete burning of the fuel; thus, 200 percent theoretical air is the same as 100 percent excess air and implies that double the stoichiometric amount of air is supplied. In general, a more complex fuel requires more excess air. Natural gas is seldom burned with more than 20 percent excess air, stoker-fired coal with between 40 percent and 60 percent, and RDF with over 100 percent excess air. A fuel heated with insufficient air decomposes and releases unburned carbon and hydrogen as soot. Because heavier fuels decompose faster than lighter fuels, soot formation is more difficult to avoid in their combustion.

Before a fuel can combine with oxygen and product heat, the molecule of fuel must first be broken into carbon and hydrogen atoms. In a mixture of gaseous fuel and oxygen, the oxygen molecules are constantly colliding with the fuel molecules. If the velocity of the molecules is relatively slow, no reaction occurs. If the velocity is fast enough that the energy generated by the collision breaks the chemical bond, combustion begins and heat is liberated. This heat increases the temperature and causes the velocity of the surrounding molecules to increase, and the reaction spreads through the mixture.

Combustion of liquid fuels is more complex. The liquid molecules are not separated from each other as in a gas, but are chemically bonded. This prevents contact with oxygen everywhere but at the surface. The liquid molecules must be vaporized by the heat of a previous combustion reaction or an ignition before they can oxidize. High speed vaporization is necessary to achieve rapid combustion. This can be accomplished by atomizing the liquid to increase the surface-area-to-volume ratio. Once the liquid has been vaporized, combustion occurs in much the same fashion as with gaseous fuel.

The combustion of a solid fuel is still more complex. The solid must be heated to drive off the volatile hydrocarbons before they can burn and remain at a high temperature for an extended time to react the fixed carbon it contains. Almost all solid fuels contain incombustible materials which will remain as ash after the combustion process has been completed. As with oil fuels, increasing the surface-area-to-volume ratio by breaking the fuel into smaller pieces generally increases the rate of combustion.

4 COMBUSTION SYSTEMS I: MASS BURNING

General

The term "mass burning" denotes the combustion or incineration of mixed solid waste in as-collected or as-delivered condition. It involves no direct processing of waste into a refined "fuel" with improved combustion characteristics, but does include use of special shredders to reduce the size or structural strength of bulky combustibles to permit them to physically pass through the incineration heat-recovery process.*

The two general categories of mass burning systems are "package" and "field-erected." Package systems (sometimes referred to as "modular" systems) are predesigned, highway-shippable units. Throughput capacities of package incinerators range upward to 18.7 MBtu/hr (19.7 GJ/hr), approximately 2200 lb/hr (998 kg/hr) for waste having a lower heating value of 8500 Btu/lb (19 770 kJ/kg). Field-erected systems are typically larger than package systems, are designed to accommodate the specific characteristics of waste at a given site, and are erected on site. While field-erected systems are about twice as costly to procure and install as package systems of equal capacity, they have a greater reliability and longer functional life.

The four types of currently available package incinerators are the controlled-air, rotary-kiln, basket-grate, and augered-bed combustor. In package energy-recovery systems, the incinerator is followed by a heat exchanger—usually a package waterwall watertube boiler with soot-blowing capability. Package boiler technology is well established; technical aspects of package boilers are reviewed here only insofar as their placement in series with an incinerator is concerned.

Several configurations of field-erected energy-recovery systems are available. These systems range from the integrated waterwall incinerator to placement of the heat exchange elements after a refractory furnace. An essential difference among current field-erected incinerators is the stoking mechanism, which is detailed in the **Field-Erected Systems** section (p 37).

Package Systems

Basic Process Flow

The process flow for package energy-recovery mass burning is illustrated in Figure 5. The essential unit operations are weighing, delivery and handling, incineration, heat recovery, off-gas cleaning, collection and disposal of ash and residue, and disposal of cooled and cleaned off-gases. Temporary storage of unprocessed waste and shredding of bulky incombustible wastes are optional system elements. A preengineered shell enclosure usually houses the incinerator plant.

The weigh station is typically located outside the plant near the entrance and may be either manned or automatic. While the installed cost of an automatic weighing facility is higher than that of a manned one, it usually proves less costly over the economic life of the plant. An automatic system may include either a standard automatic printing device or a remote-reading electronic system in

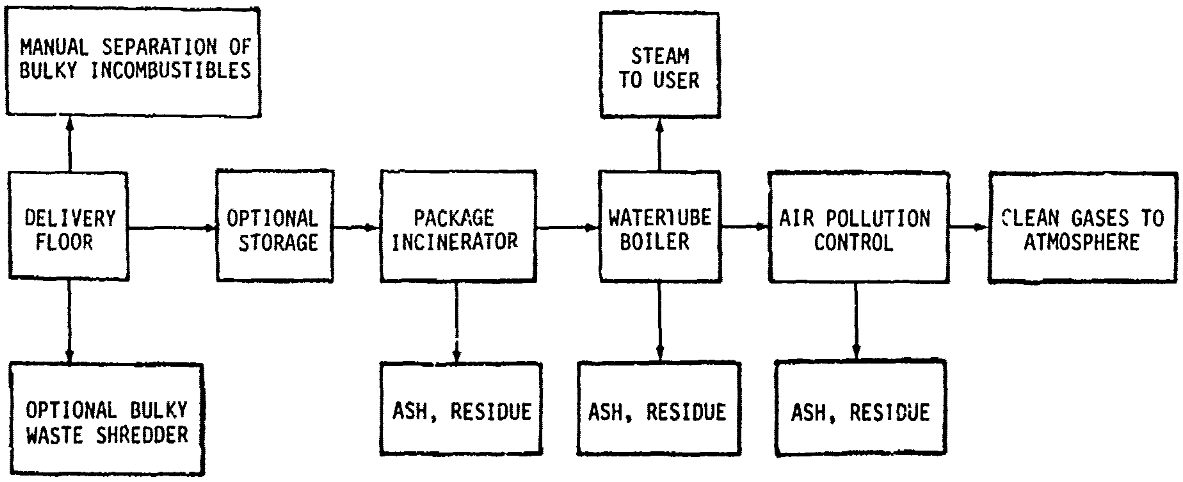


Figure 5. Typical package incinerator—energy-recovery system.

---

*Shredding is the generic term for the mechanical process of solid waste size reduction, superseding terms such as "milling" and "grinding." A "shredder" is used here to mean any shredding apparatus.

which weights are recorded in the plant control room. Installed costs of weigh stations range between $15,000 and $30,000, depending on required scale capacity and nature of recording components.

Mixed solid waste delivered to the plant may be handled in a variety of ways. For larger waste streams, a pit-and-crane system may be desirable. In such systems, waste is dumped directly into a concrete pit which is usually designed to accommodate surge/storage quantities. A ceiling-mounted grapple moves material from the pit. A system using a tipping floor and front-end loader is an economic alternative to the more costly pit-and-crane operation. In this type of system, delivered waste is dumped on the floor and moved by the loader either to temporary storage or directly to the incinerator feed hopper. Both systems are conducive to separation of bulky materials. Bulky combustibles may be diverted to a special shredder for size reduction before incineration. Pit-and-crane systems scaled for systems processing less than 100 tons/day (91 MT/day) normally range in installed cost between $70,000 and $325,000, depending on pit dimensions and the particular type of grapple and hoist system selected. In contrast, the tipping floor system requires only the front-end loader and a backup loader. Cost of increased building structural support to accommodate the crane is normally greater than the cost of increased floor area required under the tipping floor concept. Some systems using the tipping floor concept feed waste directly to the incinerator, while others use an intermediate conveying step. Steel piano hinge conveyors ranging from 3 to 5 ft (0.9 to 1.5 m) wide are used, but a penalty is paid in added capital and operation and maintenance (O&M) costs.

The numerous storage and flow problems associated with moist putrescible materials are avoided by keeping waste continuously moving through the system. Frequently, however, temporary (up to 3 days) storage may be required. Storage can be accomplished either in the receiving pit or in a specially designated area of the tipping floor.

Solid waste is fed into the package incinerator as required to operate the system at nominal capacity. Currently available package incinerators have not demonstrated long-term continuous feeding capability. Semicontinuous or batch-fed incinerators make maintaining continuity in steam production from the heat exchanger after the furnace relatively difficult.

Temperatures from the furnace may be controlled through use of an afterburner. Afterburning is usually employed to culminate the incineration process. The advantages of afterburning include completing actual combustion of the waste material, controlling particulate matter entrained in furnace off-gases, and limiting the temperature range of combustion products entering the heat exchanger.

The heat exchanger consists of either a package watertube or package firetube boiler. One recently developed system employs a modular coiled heat exchanger between the furnace and air pollution control hardware. Firetube boilers are not recommended for use in package energy-recovery systems because particulate matter entrained in furnace off-gases may deposit in the tubes, causing accelerated metal wastage, increased downtime, and higher O&M costs. In addition, the load-carrying and response characteristics of watertube boilers are superior to those of firetube units. The boiler is usually equipped with soot-blowing capability, ash hoppers beneath the gas passes, and auxiliary burners to permit direct firing with clean fuel when the incinerator is off-line. The optimal design includes bypassing air pollution control equipment when the boiler is clean-fuel-fired. Package watertube boilers with the above capabilities and in the size range compatible with package incinerators (>15,000 lb/hr [6804 kg/hr] saturated medium pressure steam) range in installed cost between $50,000 and $90,000.

Continuous ash removal capability has not been proven in most package incinerators. A large variety of ash removal systems now exist, ranging from simple forced displacement, to a pit below the end of the furnace when a new charge is batch-loaded, to semicontinuous flow, to a water quench and removal by inclined drag conveyor.

Because a given charge to the furnace can contain up to 35 percent ash, system design must anticipate high mass emission rates of air pollutants. Wet or dry air pollution control systems can be designed to effectively reduce emissions. Wet systems consume large amounts of power and create a water treatment requirement. Installed capital costs of modular wet scrubbers range between $70,000 and $110,000. Baghouses, electrostatic precipitators, and dry scrubbers are alternative dry collection systems. Recommended media for baghouses are materials such as fluorocarbon which resist high temperatures, abrasion, and most usually encountered forms of corrosion. A precipitator-based design usually includes a cyclone separator before ash storage to remove hot cinders which may cause fire or explosion.

Capital costs for precipitators and baghouses are generally comparable; in series with package incinerator-boiler systems, installed costs range between $150,000 and $250,000. Utility costs for baghouses and precipitators are also comparable. While the large pressure drop through the fabric filter increases fan horsepower requirements, the precipitator is a continuous consumer of electrical power for particle charging and collection. A precipitator system may require preconditioning of the flue gas with sulfur trioxide. Since Army solid waste contains comparatively little sulfur, the resistivity of particulates at the collection electrode may adversely affect the design collection efficiency of the precipitator.

The recently developed dry scrubber employs circulating pea gravel as a durable, temperature-resistant filtration medium. The dry scrubber has performed well in use on wood-burning boilers and appears to have great promise in incineration applications.[16] Units sized for package incinerators range in installed capital cost between $190,000 and $250,000. Annual O&M costs are lower than those of alternative dry systems.

Preparing and using solid waste as a fuel can create numerous environmental hazards. Air hoods are required for shredders whose off-gases contain up to 0.05 percent of the feed as entrained dust. High chloride emissions from the combustion process are possible, because the heavier fractions of solid waste may contain substantial quantities of polyvinylchlorides. If large quantities of plated metals are present, high concentrations of zinc, tin, cadmium, lead, and antimony are emitted as a submicron heavy aerosol formed by reducing and evaporating these metals in the fuel bed and oxidizing the vapor as it passes through the flame front. The metals either coalesce as a heavy metal aerosol or plate out on the ash matrix.[17] Because of varying resistivities, some trace metals may pass through an electrostatic precipitator.[18] By taking combustion air from solid waste delivery and storage areas, odors can be controlled effectively. Noise from shredding operations can be reduced either by properly designing the unit housing or by installing acoustic partitions, with low-resistance blast panels installed on the ceiling.

Starved-Air Incinerator

Operation. Starved-air incinerators have recently gained popularity in solid waste incineration, principally because inexpensive, small-capacity units are being manufactured. Larger package units (1.25 ton/hr [1.13 MT/hr] capacity range) are available in two different major configurations (Figures 6 through 8). These units operate on the principle that the charge is batch-fed into a primary chamber and burned in less than theoretical air. Combustion is completed in a secondary chamber to which excess air and additional heat are supplied. A well-operated starved-air incinerator will achieve between 80 and 93 percent combustion.

A drawback to the starved-air system is the lack of charge mixing. This deficiency normally prevents the material from being completely burned and often causes furnace pulsations. As a result, energy-recovery efficiencies average only 55 percent. Temperature is controlled by adding air and auxiliary fuel to the afterburner and modulating the primary combustion air supply; however, in an improperly operated unit, the carbon content of ash emitted from the furnace is often high.

Several vendors have starved-air units with semiautomatic feeders and semicontinuous ash-removal systems. Currently, however, fully automatic ash removal is not proven technology. Because of high temperature slagging in the primary chamber, the unit has a comparatively large fraction of downtime, with corresponding high O&M costs. Reducing primary furnace temperatures decreases formation of problematic "plastic" slag, but also increases the residence time required for complete combustion, resulting in unit derating by as much as 20 percent. Most available units require moderate quantities of auxiliary fuel, although recently developed combustion controls which automatically

---

[16] S. A. Hathaway and J. P. Woodyard, *Technical Evaluation Study: Solid Waste as an Energy Resource at Quantico Marine Base, VA*, Technical Report E-93 (CERL, 1976).

[17] H. G. Rigo, S. A. Hathaway, and F. C. Hildebrand, *Preparation and Use of Refuse-Derived Fuels in Industrial Scale Applications*, presented at the First International Conference on Conversion of Refuse to Energy, Montreux, Switzerland, 3 November 1975.

[18] A. McFarland, et al., *Control Technology for Toxic and Hazardous Air Pollutants*, Document 75-6 (Illinois Institute for Environmental Quality, April 1975).

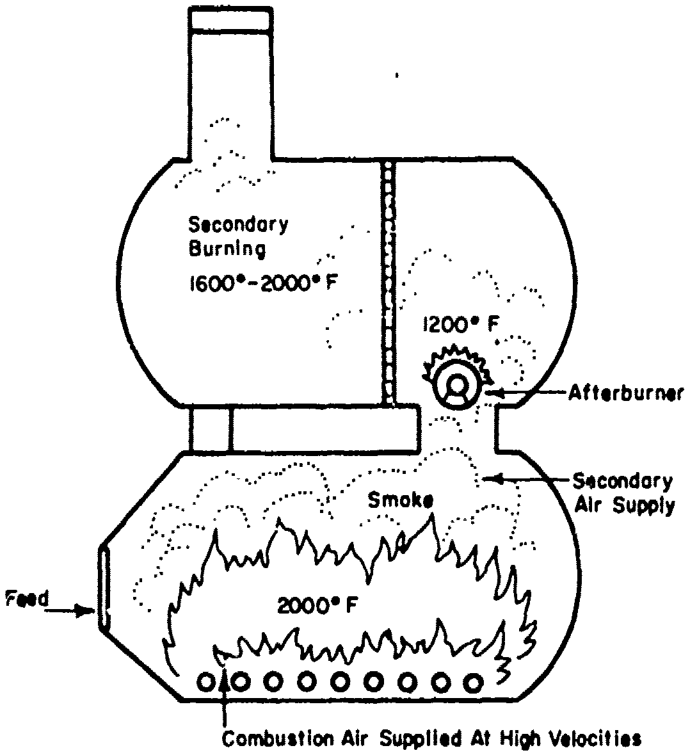


Figure 6. Starved-air incinerator (first major configuration).

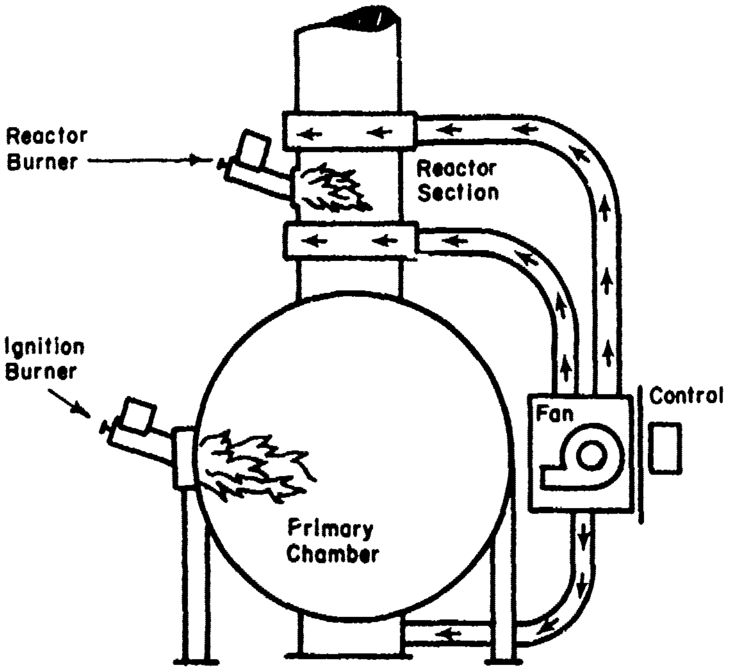


Figure 7. Front view of starved-air incinerator (second major configuration).

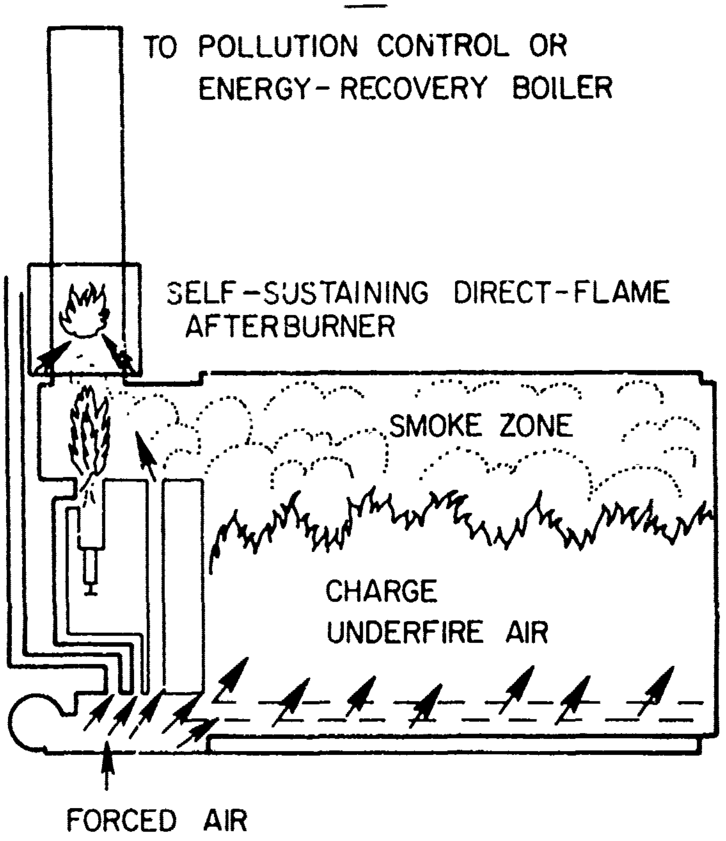


Figure 8. Side view of starved-air incinerator (second major configuration).

modulate excess air in the afterburner have reduced fuel oil requirements to about 12 gal/ton/hr (50 ℓ/MT/hr). Underfire air has been modulated in attempts to achieve constant quality of off-gases passing to the afterburner.

There are two basic starved-air incinerator configurations. The first is comprised of two "piggyback" combustion chambers, in which refuse is charged to the primary (lower) chamber through an air curtain. The entryway is surrounded by an annular ring of compressed air jets, which provide a conical blast that prevents flareback when the charging door is opened. When temperature in the primary chamber reaches approximately 600°F (316°C), a stream of air passes over the fire. Incombustible materials precipitate to the grateless bottom of the chamber, and the remaining solids, gases, and odors rise to the upper or secondary chamber where excess air is added. Thorough mixing is maintained by baffling excess air as it is added. Temperatures in the primary chamber range to 2200°F (1204°C), and usually to 1200°F (649°C) in the secondary chamber.

Most units of this configuration feature an automatic temperature-activated indicator which signals the operator when charging should begin and end. On small units, the charge is delivered manually to the primary chamber. Batch ram loaders are normally provided with larger units. Commercially available package starved-air incinerators range in capacity from 200 to 2200 lb/hr (91 to 1998 kg/hr) for waste with a heating value of 8500 Btu/lb (19 770 kJ/kg).

The second type of starved-air incinerator (Figures 7 and 8) uses a substantially smaller secondary combustion chamber. Currently available units can handle up to 2400 lb (1089 kg) per loading.

These units process the charge similarly to the units discussed above. The charge is partially pyrolyzed in the primary chamber, and the products are then passed through an afterburner located above the primary chamber. The afterburner is clean fuel fired, and promotes complete combustion of the pyrolysis products in an excess air environment. Newer models feature an afterburner fired by a mixture of pyrolysis products from the primary chamber and preheated air, which reduces clean fuel requirements.

The chief drawback to this type of starved-air system is that when the charge has been completely processed, the furnace must be shut down and allowed to cool before another batch can be loaded safely. Recent design innovations employing semi-continuous charging and ash removal have not been proven.

Installed capital cost of starved-air incinerators ranges between $80,000 and $240,000, depending on capacity, type of feed hopper, and nature of ash-removal system.

Current Technical Status. While starved-air incinerators have been commercially available for over a decade, numerous technical questions as to their applicability to Army-scale energy-recovery systems remain. It has not been demonstrated that the starved-air incinerator can operate reliably over a three-shift, week-long schedule firing typical installation mixed solid waste. When operated at high temperatures, the primary chamber will severely slag, resulting in clogging of underfire air ports, channeling of the charge, incomplete combustion, loss of overall efficiency, and deterioration and wastage of refractory material. Numerous instances of sparklers passing from the primary combustion chamber through the system to the stack have been observed in the field. In some dry ash-removal systems, burning material has been observed being ejected in the ash.

Labor intensity to operate an incinerator plant using this configuration is also of concern: loading of the ram feed hopper must be done every 8 minutes, and additional labor must be available to manually clear underfire air ports. Skin temperatures of the combustors may reach 450°F (232°C), jeopardizing plant personnel. Long-term operational data on starved-air heat-recovery systems for use in predicting performance reliability and O&M requirements on heat exchanger surfaces exposed to relatively dirty, high-temperature off-gases from the incinerator do not exist. Manufacturers' claims that the starved-air incinerator requires no air pollution control equipment are unsubstantiated insofar as the combustion of typical installation mixed solid waste is concerned. Ram feeders typically used in starved-air plants are also of concern. Fine material (e.g., sawdust) will pass through feeder construction, resulting in unnecessary plant housekeeping tasks. Ram feeders withdrawing from the furnace will often tend to drag burning materials into the feed hopper, jeopardizing plant personnel. If the starved-air incinerator is to be used, a high degree of costly hardware redundancy is required to insure continuous processing of delivered solid waste and generation of thermal energy. The starved-air incinerator has only a 2.5-year history in energy recovery applications. The system requires further testing, evaluation, and design improvement before it can be reasonably guaranteed as a reliable mass burning waste disposal/energy production means for Army utilization.

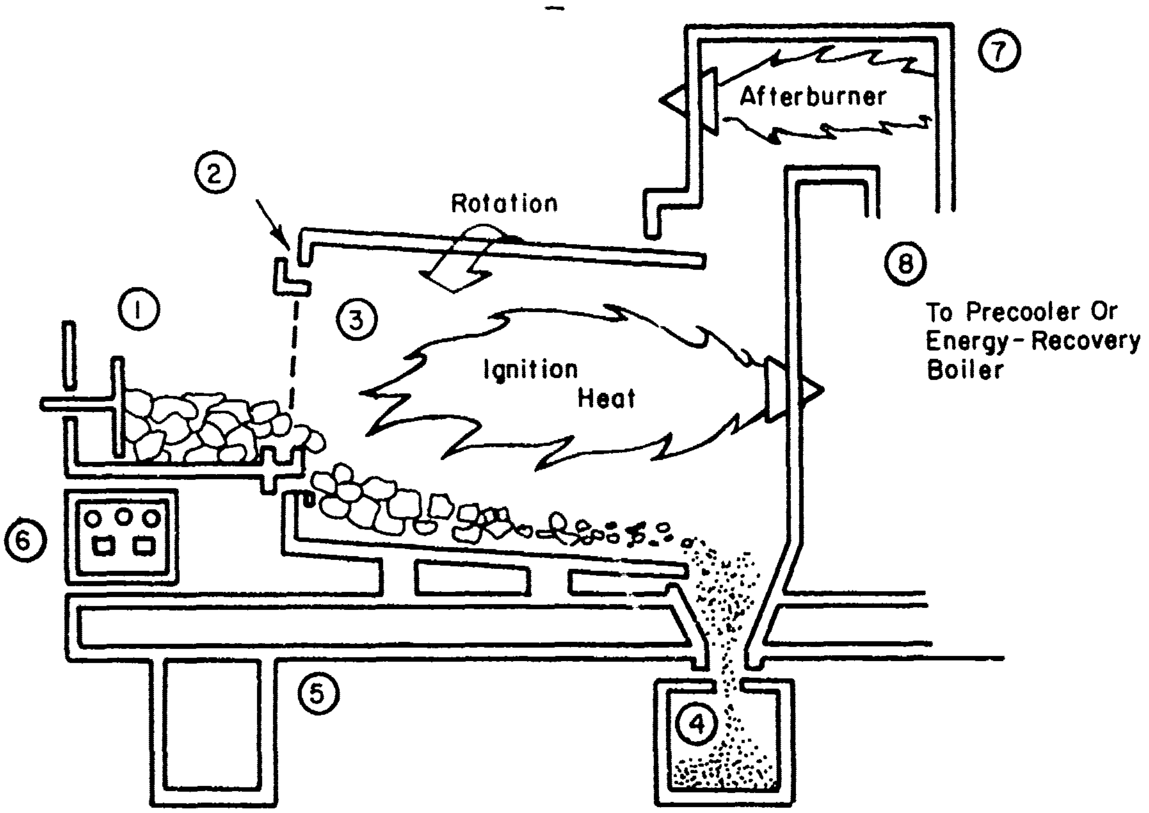
Rotary-Kiln Incinerator

Operation. The primary combustion chamber of the rotary-kiln incinerator is a slightly inclined, refractory-lined cylinder (Figures 9 and 10). In most commercially available units, the shell is prefabricated, so that the kiln may be shipped as a unit. Refractory materials are customarily made to specifications given in terms of thermal tolerance and resistance to abrasion and corrosion.

During combustion, the kiln rotates around its longitudinal axis of symmetry, continually mixing the charge mechanically as it is being conveyed to the discharge end. The constant motion effectively breaks caked layers on the charge's surface, continually exposing fresh surfaces and increasing combustion efficiency. In a well-operated unit, there is approximately 92 percent combustion. The combustible material dries quickly, ignites, and burns thoroughly. Combustion air is preheated by reflected heat from within the kiln. The ignition burner is located at the discharge end of the kiln and may be fueled with light or heavy oil, gas, or flammable liquid waste material. Temperatures sufficient to sustain ignition are normally maintained by the burning charge after startup. Additional fuel can be supplied to the kiln when wastes having a heating value too low to support self-combustion are being burned. This auxiliary fuel may be mixed with the charge or burned in either an auxiliary burner or the ignition burner.

In energy-recovery systems using the rotary-kiln incinerator, the package boiler is installed after the afterburner. The energy-recovery efficiency of these systems can range between 60 and 75 percent, including boiler and breeching losses.

The rotary kiln can burn mixed solid waste as received. Oversized bulky wastes are usually shredded to insure complete combustion within reasonable detention times. Feeders on commercially available



1 Coarse RDF Auto-Feed (Hopper, Pneumatic Feed, Slide Gates)
2 Forced Air
3 Refractory-Lined Rotating Cylinder (Primary Chamber)
4 Ash Hopper (Incombustibles)
5 Support Frame And Piers
6 Cortrol
7 Secondary Chamber
8 To Appurtenances

Figure 9. Rotary-kiln incinerator.

units are designed to accommodate feed variability. Sludges and similar wastes are usually mixed with a variable supply of solid waste before charging.

A ram feeder can be used to charge the primary chamber. Ash is continuously discharged through a port in the bottom of the refractory-lined firing hood at the end of the unit. The discharge end firing hood is equipped with labyrinth seals and heat-resistant gaskets to inhibit air leakage.

The detention time of solid material passing through the kiln is controlled by the cylinder's slope (usually 20 degrees) and its rotational speed. The velocity of gases passing through the cylinder is determined largely by combustion air requirements. Gas velocity is partially controlled by modulating the induced draft fan and damper, located after the pollution control equipment. Gases from the primary chamber pass into the afterburner section, where residual volatiles are combusted in an oxygen-rich atmosphere.

Automatic temperature controls are used. A primary pyrometer monitors the temperature of gases leaving the kiln. When the exist gas temperature fails below a predetermined set point, gas flow to the burners increases. A second control monitors gas temperatures in the afterburner. When the afterburner temperature falls below the set point,

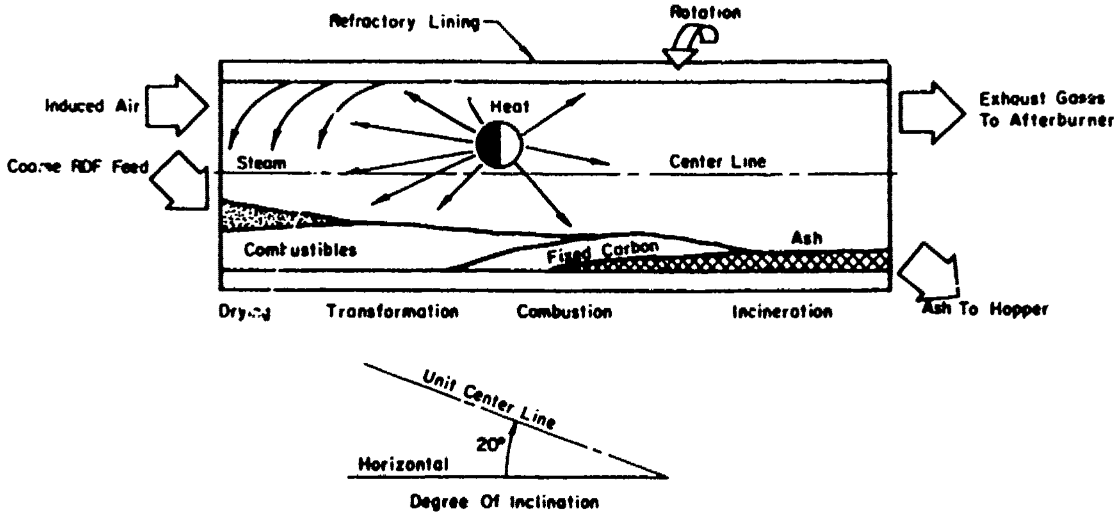


Figure 10. Operation of rotary-kiln incinerator.

the burner heat release increases. When the temperature exceeds the upper set point, the burner automatically modulates downward. An additional optional temperature control apparatus from a gas precooler shuts down the burners, fan, and feeder when gas temperatures exceed a safe upper limit. An alarm in the control module activates after safety shutdown.

Rotary-kiln incinerators normally operate with 140 percent theoretical air in the primary chamber. Operating temperatures in the kiln are usually between 1400°F (760°C) and 2300°F (1260°C), with a recommended operating range between 1200°F (649°C) and 2400°F (1316°C).

Due to thermal losses and the addition of excess air, the temperature of gases leaving the afterburner section normally ranges between 1500°F (816°C) and 1880°F (982°C). If these gases must pass directly to the air pollution control equipment, they must be precooled by a water spray, addition of tempering air, or a heat exchanger. In the latter case, recovered heat may be used t[illegible]eat combustion air or be used elsewhere in th[illegible]ing plant.

Bottom ash and residue drop into a water-sealed ash-handling unit below the kiln. A grate is sometimes placed in front of the bottom ash-handling hardware to trap oversized combustibles such as cans and pipes, but this can cause exit blockage and ash backup. If the bottom ash is sufficiently fine, water-cooled screw augers can be used for ash removal.

Some available rotary-kiln incinerators are equipped for either counter-current or gas/charge flow (Figure 11). Concurrent flow is used for drier, more heterogeneous wastes. Volatile matter driven from the charge is completely burned in the afterburner section, permitting higher thermal loading in the combustion zone. Counter-current operation is suitable for incinerating sludges. Combustion products are used to dry the incoming charge, permitting higher combustion efficiency.

Installed capital cost of rotary-kiln incinerators ranges from $150,000 to $500,000, depending on capacity and type of feed and ash-removal system employed.

Current Technical Status. The rotary-kiln incinerator has been commercially available for over a decade, and numerous package systems are currently in use. However, few operating data pertaining to total system performance in heat-recovery applications exist; manufacturers are hesitant to recommend using the kiln in an energy-recovery

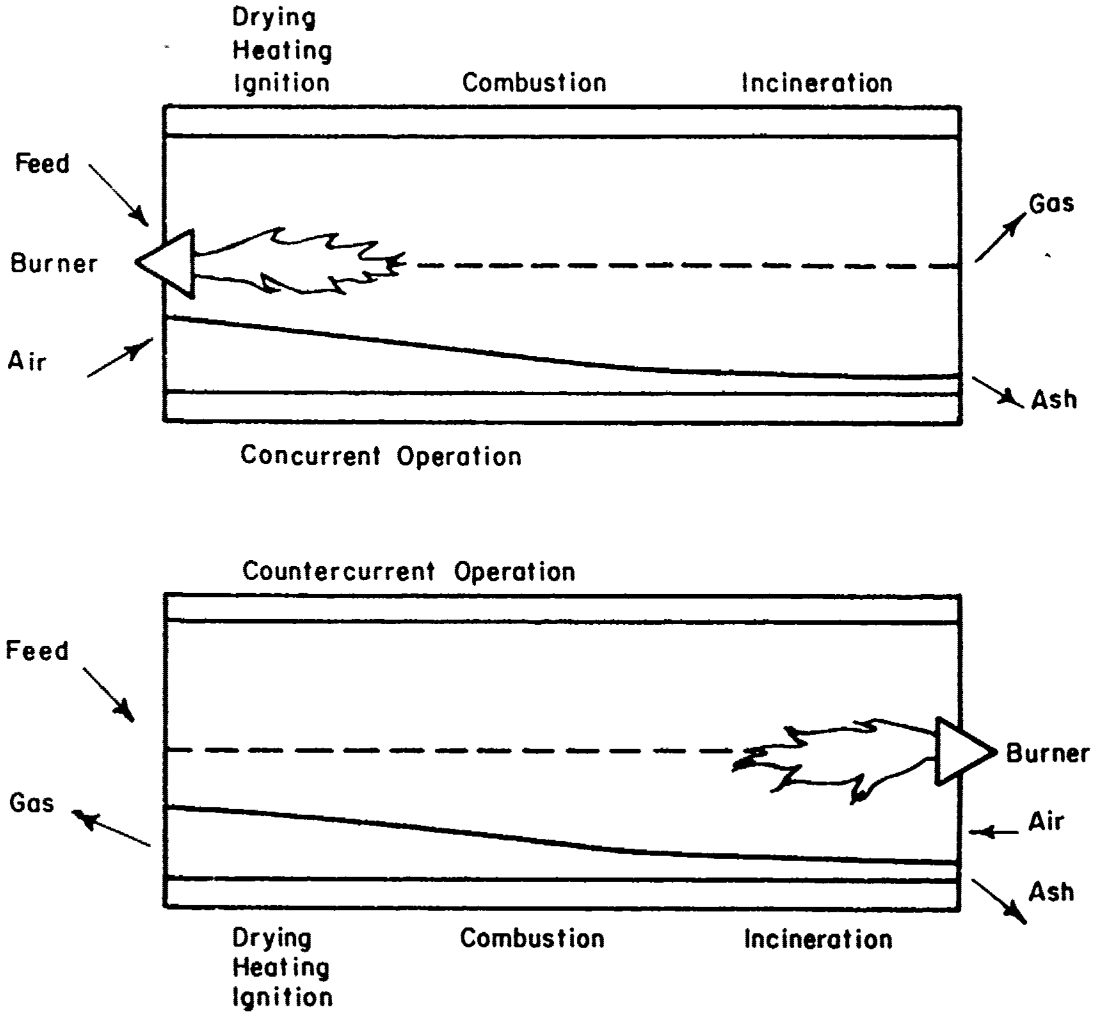


Figure 11. Concurrent and countercurrent operation of rotary-kiln incinerator.

application principally because of operational unknowns related to the heat exchanger. The combustor itself, however, has numerous theoretical advantages. Although it consumes more electrical power than stationary grate incinerators of equal capacity, it appears to be technically superior in its mixing and continuous material throughput capabilities.

The comparatively higher capital cost of this unit may be more than offset by the tangible advantages of improved combustion efficiency and lesser maintenance requirement over its functional life. Such tradeoffs are currently only speculative, however.

The reliability of the rotary-kiln incinerator is currently unknown. However, its technical superiority makes its potential for installation use greater than that of stationary grate systems. The rotary-kiln incinerator cannot be recommended for solid waste incineration with unqualified confidence. In heat-recovery applications, any recommendation must be tempered by unknown factors relating to the effects of furnace off-gases on the heat exchanger, air pollution control requirements, and the rate of refractory wear due to abrasion and thermal stress.

Augered-Bed Incinerator

Operation. Although the augered-bed incinerator is a very recent and therefore unproven development, successful demonstrations indicate that engineering problems may be relatively minor. Units [illegible] expected to go on-line within a year, and ex[illegible]e soon thereafter will provide the operati[illegible] data necessary for improved design. Currently, manufactured package units have capacities of 1 and 5 tons/hr (0.9 and 4.5 MT/hr).

The augered-bed incinerator is comprised of a refractory-lined cylindrical primary combustion chamber that contains an auger (Figure 12). The chamber is fed continuously by inclined feed conveyor. Combustion takes place in an excess air environment as the auger conveys the charge through the length of the chamber. High-termpature combustion products pass through a coiled heat exchanger where steam is produced. Gases are then cleaned in a wet cyclone before passing from the stack. Ash removal is automatic and continuous.

The unit is capable of processing mixed solid waste as delivered. Oversized bulky materials too large to pass through the feed port are separated from the delivered waste. Waste streams containing a high percentage of bulky materials can be accommodated by adding a shredder between the delivery point and the feed hopper.

Processing is continuous. Solid waste enters a floor-level hopper and is moved on an inclined conveyor to the charging end of the primary chamber. The charge burns as the slowly rotating auger moves it through the primary chamber. The auger conveys ash and residue out the discharge end of the chamber to a chain belt conveyor, which transfers the mostly sterile, inert end product to temporary storage before ultimate disposal.

The auger is a hollow spiral flight carried by a tubular shaft. Combustion air is introduced into the downstream end of the primary chamber and forced through an air passage extending along the length of the spiral flight. Forced air passes from the flight interior into the primary chamber and is discharged as combustion air within the charge being conveyed by the auger. A water passage in the spiral flight cools the auger. The air then enters the upper portion of the primary chamber where off-gases are completely burned in a second combustion zone. A well-operated unit achieves approximately 93 percent complete combustion.

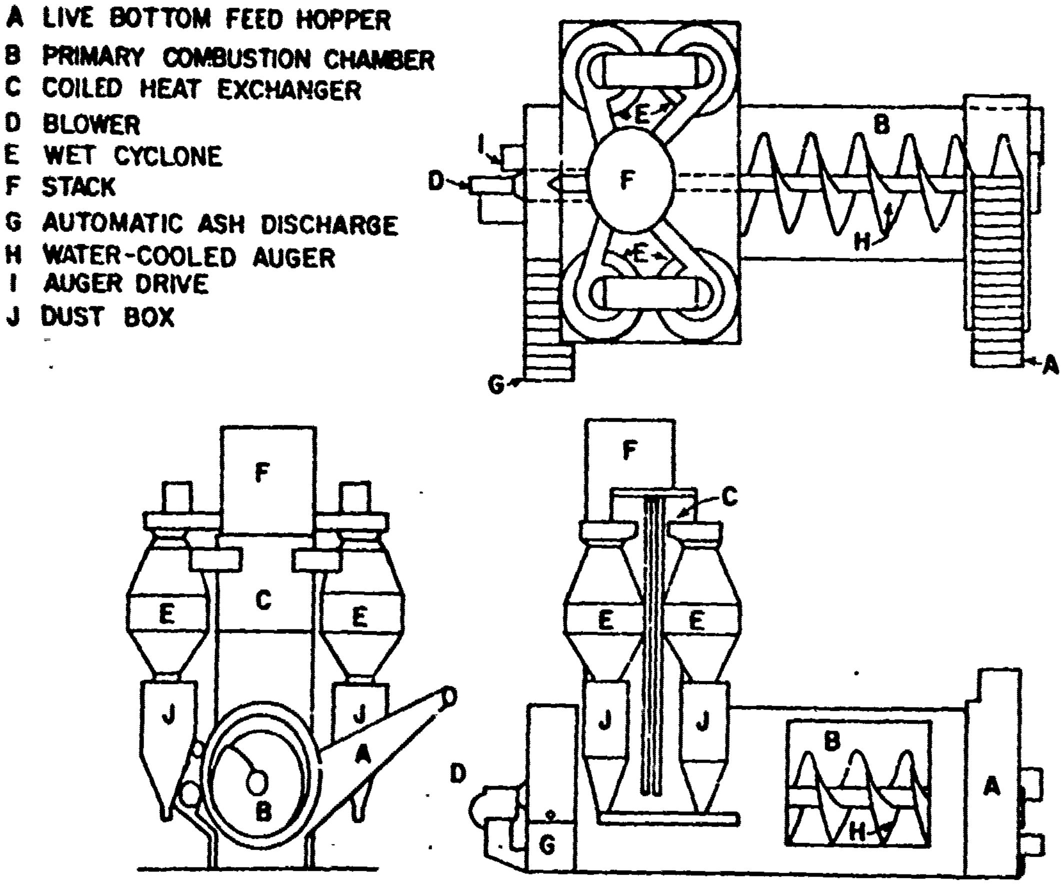


Figure 12. Augered-bed incinerator.

An ignition burner is located at the charging end of the primary chamber. Gas or fuel oil is normally used, but flammable liquid wastes can also be fired. In normal operation, the ignition burner operates only during startup, which requires about 15 min. When combustion becomes self-sustaining, no auxiliary fuel is required. The unit can be shut down in 20 min.

High-temperature combustion products pass through a coiled heat exchanger between the primary combustion chamber and the air pollution control equipment. Saturated steam is produced from water preheated in the spiral flight.

Available units include induced-air, counterflow wet cyclones for air pollution control as part of the package system.

Variable drive controls are provided on all functions to adapt to fluctuations in the type and quantity of solid waste being processed. Hydraulic drive systems are provided for the auger, feeder, and ash removal apparatus, and standard belt drives are provided for blowers. Capital cost for an augered bed incinerator rated at 1 to 4 ton/hr (0.9 to 4 MT/hr) is approximately $500,000, including heat exchanger and air pollution control.

Current Technical Status. Operating experience with the augered-bed incinerator will provide data for improved design. Data are required concerning possible fouling and tube metal wastage in the heat exchanger section caused by exposure to combustion process emissions; steam production performance; results of exposing the auger material to continued thermal stress; extent of treatment required for heat exchanger feedwater and sludge from the air pollution control equipment; degree of maintenance required; quantity of clean fuel consumed by the unit in normal operation; and long-term effects of material abrasion on the refractory.

The computed energy-recovery efficiency of this system is 65 percent; operating experience is required to determine whether this is an accurate design parameter.

At its current stage of development, the augered-bed incinerator cannot be recommended as a proven waste disposal/energy production means. However, the advantages of superior process control, minimal labor requirement, and throughput capacity greater than other package systems encourage accelerated test and evaluation of the system to determine its suitability for installation use.

Basket-Grate Incinerator

Operation. Like the previously discussed units, the basket-grate incinerator (Figure 13) is designed to fire mixed solid waste as delivered. Available units have input capacities ranging between 160 and 6000 lb/hr (73 to 2722 kg/hr) of waste with a heating value of 8500 Btu/lb (19 770 kJ/kg). The primary chamber is an inclined (30 degree), truncated cone-shaped grate supported by an externally driven frame. The chamber is insulated, and the shell is fabricated of structural steel plate.

The basket grate is semicontinously charged with material to approximately 20 percent of its total volume and rotated slowly around the cone centerline. The inclination and rotation cause heavier materials to fall toward the larger (outer) basket diameter and the smaller materials to fall toward the smaller (inner) diameter. The three-dimensional self-raking effect of the virtually endless grate maximizes mechanical and thermal destruction of the charge.

The charge is retained on the grate until it can pass through the grate slots (about 0.125 in. [3.18 mm]) into an ash hopper or secondary incineration chamber. Large incombustibles can be removed periodically from the grate using a grated plate which can be lowered from the basket bottom. Some problems have been experienced with bulky incombustibles accumulating in the cone, thus reducing available combustion volume, and with fine combustibles sifting through the grate and burning in the ash hopper. Negative relative pressure within the primary chamber induces air through the ash collector, so that ash and residue leakage is not a problem. An external fan mounted on the swivel frame supplies primary air to the furnace. Distribution pipes divert a portion of the air directly beneath the firebed to provide underfire air. Part of the combustion chamber is located above the firebed, which causes a turbulence zone that effects efficient mixing and combustion. Afterburning is normally self-sustaining. Gases leave the secondary combustion chamber through the crown.

Temperatures in the secondary chamber range between 1500°F and 2100°F (816°C to 1149°C). In energy-recovery applications, the afterburner is

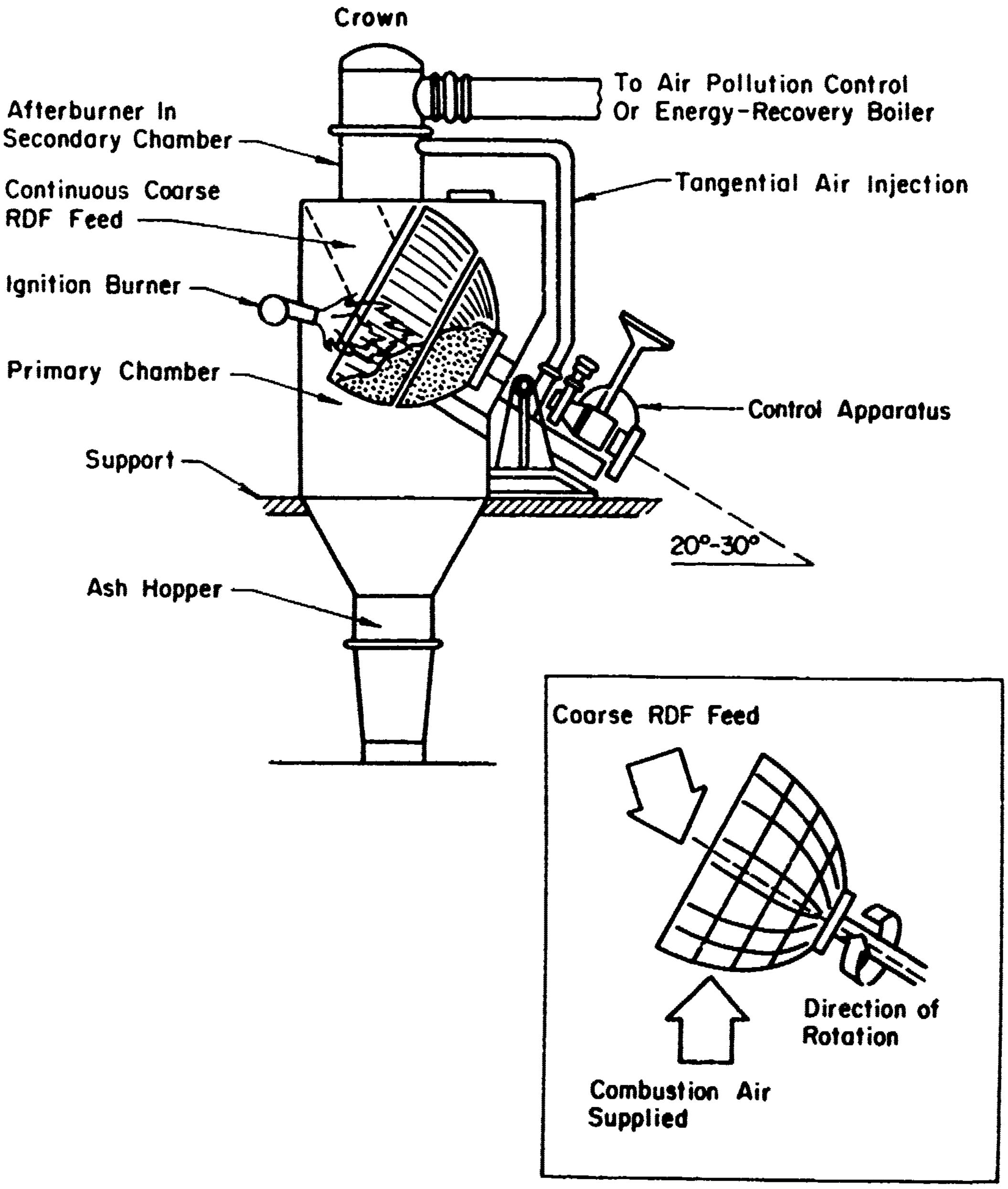


Figure 13. Basket-grate incinerator.

fired to maintain high temperatures in the gases before they leave the exit port and pass to the heat exchanger. Temperature is controlled by automatically varying the quantities of air entering the primary and secondary chambers in an inversely proportional manner. In normal operation, high off-gas temperatures can be maintained at approximately 70 percent excess air. Auxiliary fuel is usually required only during startup, which can be completed in 15 min. After the unit has been brought on-line and stabilized, no additional fuel is necessary.

Available units achieve 90 to 96 percent reduction of combustible materials for waste with a heating value of 8500 Btu/lb (19 770 kJ/kg). The quantity of incombustible residue remaining in the ash rarely exceeds 5 percent. Because the unit is designed to maximize combustion, energy-recovery efficiencies average 68 percent.

Capital costs of the unit range to $500,000 (3 ton/hr [3 MT/hr] capacity), including the heat exchanger.

Current Technical Status. The inherent engineering flaw of the basket-grate incinerator is the grate itself. Bulky incombustible materials accumulate, reducing effective combustion volume until the unit is shut down, cooled, and manually cleaned out. Fine combustibles tend to sift through grate spacings and burn in the ash hopper below. At its current stage of development, the basket-grate incinerator is not recommended as a reliable waste disposal/energy production method based on mass burning. Whether further testing of the unit will produce suitable improvements in fundamental engineering shortcomings is questionable.

Field-Erected Systems

General[9]

If large quantities of refuse are being handled, many parallel packaged units may be required to obtain the necessary plant capacity. In this situation, a large field-erected unit may be more practicable. Since each unit is designed to process a particular waste, its operation can be closely matched to site-specific needs. The size of current plants varies greatly. Several German plants process only 200 to 250 tons/day (180 to 225 MT/day) producing 45,000 to 50,000 lb of steam/hour (20,000 to 23,000 kg/hr). The Chicago Northwest incinerator burns 1600 tons/day (1450 MT/day) and produces 440,000 lb of steam/hour (200,000 kg/hr). The capital cost of these plants ranges from $2.5 to $33 million. The steam produced by refuse incineration plants is used to run plant auxiliaries and turbogenerators as well as for heating and industrial processes.

Basic Process Flow

The basic process flow of existing civilian-municipal field-erected mass burning systems is as follows. Refuse collected from households, businesses, and industries is delivered to the incineration plant by truck. Generally, these are packer trucks which compact the refuse somewhat but otherwise do not process it. (In some operations, notably Munich-South and Frankfurt-am-Main in Germany, collection trucks are equipped with shredders so that the refuse has already been partially processes when it reached the plant; this eliminates the need for plant personnel to sort the bulkies from the refuse for shredding.) A weigh station is provided near the tipping area for accounting purposes. Basic considerations are dust control and sufficient space to avoid extensive backing up by delivery trucks.

Because delivery is irregular while the feeding process is steady, storage must be used to equalize the two flows. A storage system not only protects the incinerator from fuel shortages during slow delivery periods, but also allows uninterrupted refuse collection during short-term breakdowns in the plant. Most plants have storage areas sized to hold 2 to 3 days' average refuse collection. Delivery to the plant is usually on an 8 hr/day, 5 day/wk basis, while incineration is continuous. Storage areas must have provisions for dust and odor control as well as fire-fighting equipment.

Storage areas are usually one of two types. The first, less commonly used in large-scale operations, is a tipping floor and front-end loader arrangement. Delivery trucks dump refuse directly onto a nearly flat concrete floor; floors have a slight grade to allow excess moisture to run off. Front-end loaders are then used to sort out the bulkies and feed the furnace hopper. The second type of storage area is the pit-and-crane method, which is used in almost all current operations. A large rectangular pit is provided for collection vehicles to dump their loads into. An overhead traveling crane then sorts out the bulkies and mixes the refuse before feeding it to the

---

[9] R. Schwieger, "Power from Waste," *Power* (February 1975).

furnace hopper. The usual method of dust and odor control in both handling systems is to draw the furnace air from the delivery-storage area, allowing a constant inflow of fresh air.

The pit-and-crane system is preferred in large-scale systems, since the crane operator has good control over the mixture of refuse entering the hopper and because the pit requires less floor area than a tipping floor of equal capacity. Due to frequent crane maintenance requirements, the added initial cost of a second crane for backup may be offset by the benefits of sustaining plant operation when one crane is down. The main disadvantages of the pit-and-crane system is the high initial cost. A pit-and-crane system for a 400 ton/day (360 MT/day) plant would cost about $400,000 and a second crane would cost an additional $200,000. A tipping floor and front-end loader for the same plant would require only about $150,000.

All of the field-erected incineration plants evaluated in this study separated the bulkies from other refuse before incineration. Physically, such materials cannot pass through restrictions in the incinerator, and required burnout time would be excessive if they could be charged into the furnace. Removal is handled by crane, front-end loader, fork truck, or, in a few cases, by hand. The trend is for these bulkies to be fed through a shredder with the more manageable product being returned to the storage area for incineration with the other refuse. Hammermills are the most popular shredder type, although a few plants use grinders or crushers. Shredding large appliances requires a large hammermill with a power requirement around 100 hp (74.6 kW). Capital costs of large refuse shredders range between $200,000 and $500,000.

The next operation in the process flow is feeding. Refuse is removed from the storage area by crane or front-end loader and placed in the nearby charging hopper. It then falls through a chute to a hydraulic ram which feeds the stoker. Chutes are often water-cooled to prevent damage in case of flashback. The ram must spread the refuse evenly across the width of the stoker for efficient operation. Most stoker manufacturers offer feed systems compatible with their stoker.

The purpose of a stoker is to introduce the fuel into the furnace and promote complete combustion. Mechanical mixing and agitation of refuse are beneficial to total and rapid combustion, but too much agitation disrupts the fuel bed and produces excessive amounts of entrained fly ash. A stoker must also allow underfire combustion air to pass through and must have a variable speed to handle changing qualities of refuse. Several manufacturers offer stokers designed for refuse incineration, some of which are discussed under *Stoking Mechanisms*, p 40.

The final stage in the combustion process is afterburning. This stage burns remaining combustibles in furnace off-gases, maintains desirable temperatures in heat exchange sections, and can be employed to direct-fire the heat exchanger when the furnace is off line.

The boilers, superheaters, economizers, and air preheaters used in energy-recovery refuse incineration are very similar to those used in other methods of steam generation. Large excess air requirements when burning refuse can lead to high gas velocities in the convection section and rapid erosion of heat transfer surfaces. To counteract this effect, tube spacings are large and tubes are arranged in line rather than staggered. Even so, tube wastage is a much greater problem in refuse incinerator boilers than in fossil fuel plants. The presence of corrosive gases and large amounts of fly ash are contributing factors. Several methods are used to minimize the problem. Keeping the temperature of gas flowing through the tube section low (below 800°F [427°C]) helps prevent slagging on the tubes. Routine cleaning methods also play an important role in determining tube life. Early plants used shot cleaning, which added to wastage problems significantly. Soot blowers and mechanical rappers and vibrators have proven to be much more acceptable methods of keeping fire-sides of tubes free of buildup. Many types of surface coatings have been tried with varying degrees of success. Water-side damage can be greatly reduced by judicious treatment of feedwater.

Incineration of refuse generates a substantial amount of ash and clinker. Residue will accumulate at and must be removed from beneath the grate, the residue discharger at the end of the grate, and fly ash hoppers at the boiler, economizer, and air cleaners. Removal must use a minimal amount of manpower. Residue is usually water-quenched and drained before it is moved to a temporary storage area or directly to trucks for disposal. Many installations include a magnetic separator to remove ferrous material from the residue, in spite of the low prevailing price of scrap iron and steel. A separator sized to handle 45 tons/hr throughput (41 MT/hr) ranges in cost between $30,000 and $55,000.

Due to constant variations in the nature of refuse burned, extensive monitoring and control of plant operations are essential for efficient operation. The operator should know temperatures and pressures throughout the furnace and steam system as well as refuse feed conditions at all times. Control of feed rate, grate speed, and overfire and underfire air flow rates must be exercised to keep the plant operating optimally. Monitoring and control methods vary greatly from plant to plant; some rely heavily on operator skill, while others use largely computerized controls. A recommended design will require a minimal amount of costly manpower and rely less on unpredictable operator skill than on automation.

Pollution control at field-erected plants is basically identical to that at packaged plants discussed earlier. Most existing plants employ electrostatic precipitators successfully.

Furnace Configuration

Probably the simplest furnace design is the refractory wall furnace (Figure 14). The walls of this type of furnace are lined with a high-temperature material to prevent heat from escaping. Hot gases pass upward out of the furnace to the boiler section where all of the heat exchange takes place. Since the walls are not cooled, high temperatures are reached; these temperatures, the presence of noxious gases, thermal shock, and mechanical friction can cause accelerated deterioration of materials, requiring a great deal of maintenance. The high temperatures in refractory furnaces do provide the advantage of more efficient combustion. The separation of combustion and heat transfer processes in refractory wall furnaces generally allows better control and, hence, more efficient operation.

Refractory wall furnaces are not used to a great extent in refuse incineration. Merrick, NY, has a refractory furnace burning 600 tons/day (545 MT/day) and producing 4.9 million lb (2.2 million kg) of steam/day, and Miami, FL, has a plant burning 900 tons/day (818 MT/day) and producing 750,000 lb (340,000 kg) of steam/day. Both of these plants use batch feeding methods. The Chicago Southwest incinerator plant burns 1200 tons/day (1010 MT/day) in two field-erected rotary kilns and produces 900,000 lb (410 000 kg) of steam/day. Other units are located in Fort Lauderdale and Dade County, FL. A scaled-down incinerator rated for 54 tons/day (49 MT) at the Eastman Kodak plant in Rochester, NY, has been operating successfully for 5 years.

Water wall furnaces are much more widely used. In this arrangement, the furnace walls are lined with water tubes, and a boiler section is placed after the furnace. Early designs placed the tubes tangentially to each other, while more recent designs separate the tubes with a steel bar (membrane wall construction). Water tubes are often fitted with fins or studs to improve heat transfer and reduce gas turbulence at the tubes. Keeping the tube temperatures above the dew point of furnace gases prevents condensation of corrosive substances and results in

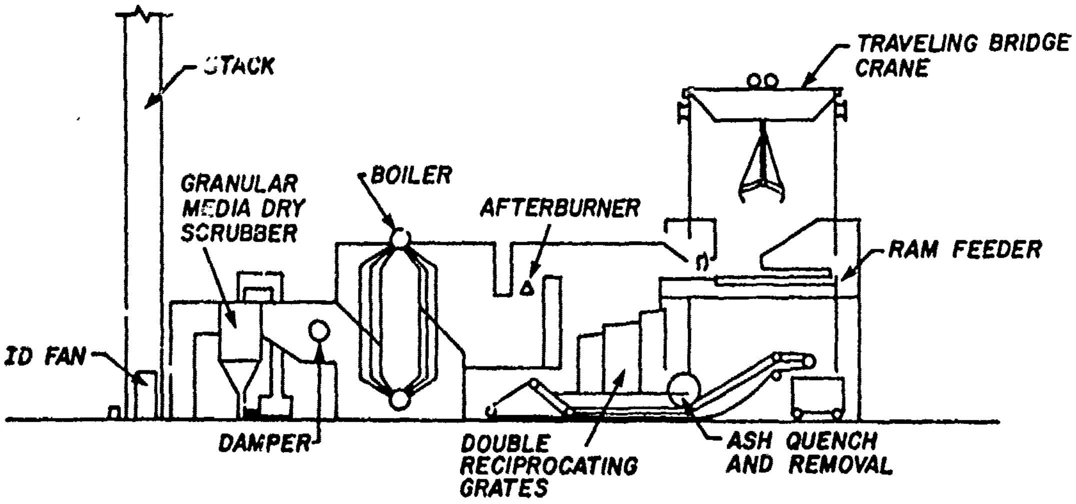


Figure 14. Refractory wall heat-recovery incinerator.

fewer failures. When heating values of fuels are high, more air than is actually necessary for complete combustion is added in refractory furnaces to keep the wall temperature from becoming excessive. This is unnecessary in waterwall furnaces, since large amounts of heat are transferred through the tubes to the water. Comparatively smaller gas volumes pass through the convection section, reducing wastage and air cleaner loads. Also, temperatures in the convection section are lower due to removal of heat in the furnace section, reducing the potential for problematic slag formation. A considerable amount of maintenance is required for waterwall tubes.

Waterwall furnaces are used with a high degree of success in almost all currently operating large-capacity plants. The Dusseldorf, Germany, plant has been successfully incinerating 270 tons/day (245 MT/day) in waterwall furnaces since 1965. The first application of this configuration in the United States began operation in 1967 at Norfolk, VA. This plant was designed to burn 360 tons/day (327 MT/day) and to produce 100,000 lb (45 000 kg) of steam/hr at complete load.

Stoking Mechanisms

Batch stokers are not well suited to large-scale operations because the charging cycle produces corresponding variations in temperature and heat supplied, thus putting an unnecessary strain on all elements of the system. Because of this undesirable characteristic, batch stokers will not be further discussed.

The simplest type of continuous stoker is the traveling grate (Figure 15). This system, which was designed to fire coal, uses an endless grate to move the refuse through the combustion chamber. No provision is made for mixing or turning the refuse, so burning is relatively poor and grate surface area must be large to achieve burnout. These grates have the advantage of simple construction and low initial cost. The Norfolk, VA, incinerator uses this system.

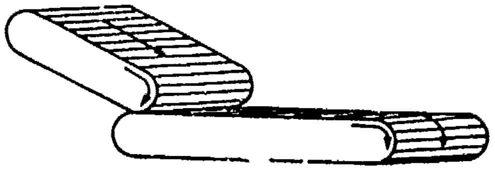


Figure 15. Conventional traveling grate.

Rocker-action or step-tilting grates (Figure 16) have been developed for the combustion of hard-to-burn materials. The grate surface is comprised of 10 to 18 stages which are controlled by separate drives. The tilting action of the grate sections provides effective circulation of the material, and individual controls allow careful regulation of the fuel speed through the combustion chamber. Combustion occurs rapidly, allowing grate area and furnace size to be reduced. A major problem with this stoker system is undergrate fires caused by fine burning material sifting through the grate spaces, which are wider in this system than in others discussed here. No standard rocker-action grate design is presently commercially available for waste incineration.

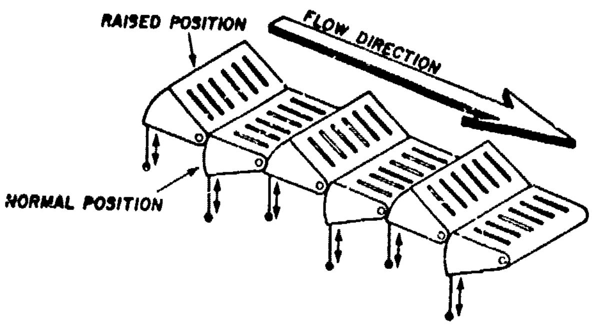


Figure 16. Rocking grate stoker.

The reciprocating stepped-down grate (Figure 17) has been used for some time in Europe and has several current applications in Canada. The usual configuration includes three separate tiers. The first is a drying grate, inclined at about 20 degrees. Located 5 ft (1.5 m) below the discharge of this grate is the burning grate, inclined at about 30 degrees. This grate is often equipped with mobile knives to mix refuse. Five ft (1.5 m) below the discharge of this grate is the burnout grate, also inclined at about 30 degrees. Good mixing is obtained by the reciprocating action of each grate and by tumbling between grates. Underfire air can be effectively zoned, and openings constitute only a small portion of the total grate area, minimizing siftings and undergrate fires. The Von Roll Company of Zurich, Switzerland, has installed this grate system in many plants in Europe and achieved satisfactory operation. Capacities range from 130 tons/day (118 MT/day) in Lucerne, Switzerland to 1200 tons/day (1100 MT/day) using four units in Montreal, Canada.

A recent improvement is the double reciprocating

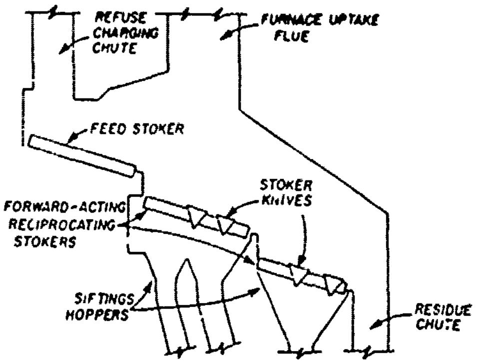


Figure 17. Von Roll grate system.

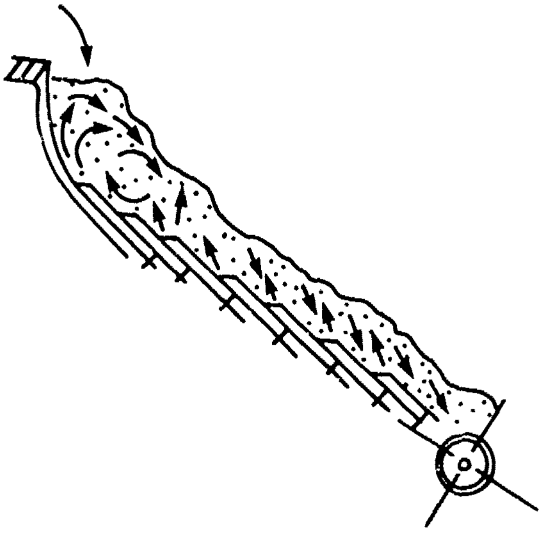


Figure 19. Reverse reciprocating stoker.

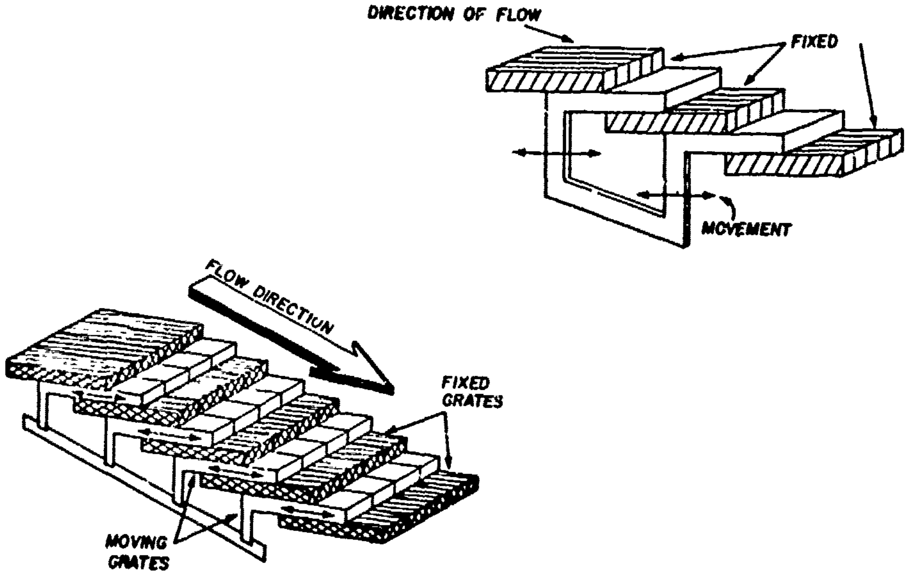


Figure 18. Double reciprocating grate stoker.

grate (Figure 18), which has been designed to provide added mechanical mixing of the waste, thereby improving combustion performance.

Another proven stoker is the reverse reciprocating grate (Figure 19). This grate is a stepped-down design, inclined at about 30 degrees towards the discharge. Heavy, serrated cast iron grate bars are keyed to a structural frame. The keys push uphill in a reciprocating action against the flow of the waste. With every stroke, a portion of burning material is pushed under new refuse. A short relative motion between bars frees debris from the air spaces. Bed thickness is controlled by modulating both feed rate to the forward end and a variable speed discharge drum. The Josef Martin Company of Munich, Germany, has been producing this type of grate for refuse incineration since 1966 and it has been widely accepted for its reliability and efficiency. The Chicago Northwest incinerator uses four Martin grates to burn 1600 tons/day (1450 MT/day) of municipal refuse.

The drum grate system (Figure 20) has also been used in the field for several years. This grate is usually comprised of seven cylinders, 5 ft (1.5 m) in diameter and 10 ft (3.0 m) long. The cylinders are arranged tangentially to each other with their axes horizontal and perpendicular to the flow of refuse. The row is sloped about 30 degrees toward the discharge end. Each drum is constructed of serrated bars of gray cast iron and each is positioned above a separate compartment for zoning of underfire air. Drum speeds are adjustable from 50 ft/hr (15 m/hr) for the first drum to 16 ft/hr (5 m/hr) for the discharge drum. This grate produces the most efficient combustion with the smallest grate area, but the cost is 2.5 to 3 times that of other grates. Known as the "Dusseldorf system," a grate of this type was designed by Vereingte Kesselwerke A.G. and first put into operation in 1965. They are produced in this country by Erie City Energy Division of Zurn Industries, Inc., a licensee of V.K.

Reilly Slag-Forming Incinerator[20]

A new furnace concept illustrated by Figure 21 is currently under development. The two-stage slag-forming incinerator consists of a conventional refractory lined furnace which uses excess combustion air to hold the temperature below the slag-forming limit of about 1800°F, plus a slagging furnace which uses part of the hot, oxygen-rich off-gas from the conventional furnace to incinerate the final 20 to 40 percent of the combustible refuse.

The primary combustion chamber is undersized in comparison with conventional incinerator design practice. The short, inclined grate provides residence time for only 60 to 80 percent complete combustion of the combustible refuse fed into the furnace. The unburned fraction and other solid residue from the primary chamber falls from the grate to the slagging furnce below, where combustion continues.

The primary chamber feed system, temperature control system, and general design are identical to those of present plants that have been operating successfully for 3 years or longer. The ram feeder meters refuse from a storage hopper at a controlled rate into the furnace, where it is aerated with high-pressure jets and tumbled to a reciprocating grate. Combustion air is provided by two forced-draft fans; one supplies the underfire air requirement while the other provides air to a series of overfire jets. The overfire jets not only provide turbulence, which is essential to good combustion but also dilute and cool the furnace gases to prevent overheating the primary chamber.

The combustion products from the primary chamber divide to flow either through the slagging furnace or through a damper-regulated bypass breeching. The bypass damper is water-cooled and refractory-lined to endure the 1800°F (982°C) flue gas. Since all the flue gas from the primary chamber must go through one of the two passages, closing down the bypass damper increases the gas flow through the slagging furnace, and opening it decreases the slagging furnace gas flow.

The slagging furnace is thus fed with hot, partially combusted refuse and hot (1800°F [982°C]) oxygen-laden off-gas, which combine to liberate additional heat. The design of the slagging furnace —the only new, untried part of the process—is aimed at accomplishing three functions: (1) providing the extended residence time required to complete the combustion of the refuse which was not consumed in the primary chamber; (2) providing a temperature-resistant enclosure which is not only insulated from outside atmospheric temperatures, but is also shielded to minimize radiation losses from the slagging furnace to the primary chamber and connecting flues; and (3) providing sufficient gradient to the furnace hearth that the molten residue and ash will flow to the exit port and into the quench tank.

There are conservative estimates of the heat balance which would be developed between an 1800°F (982°C) primary chamber and a 2800°F (1538°C) slagging furnace for varying operating conditions. A rather wide operating band exists. Satisfactory heat balances appear attainable for a range from 60 percent primary combustion plus 40 percent slagging furnace combustion to 80 percent primary combustion plus 20 percent slagging furnace combustion. This balance holds for refuse of varying moisture contents. Throughout this range, the slagging furnace gas will still contain some excess oxygen after completion of its combustion process. No credit has been taken in the heat balance estimates for the probable combustion of carbon monoxide to carbon dioxide in slagging furnace. The primary chamber, as noted earlier, is

---

[20] *Refuse Incinerator/Heat Reclamation Boiler Facility, Naval Station Mayport FL* (Greenleaf/Telesca, Planners, Engineers, Architects, Inc., 1975).

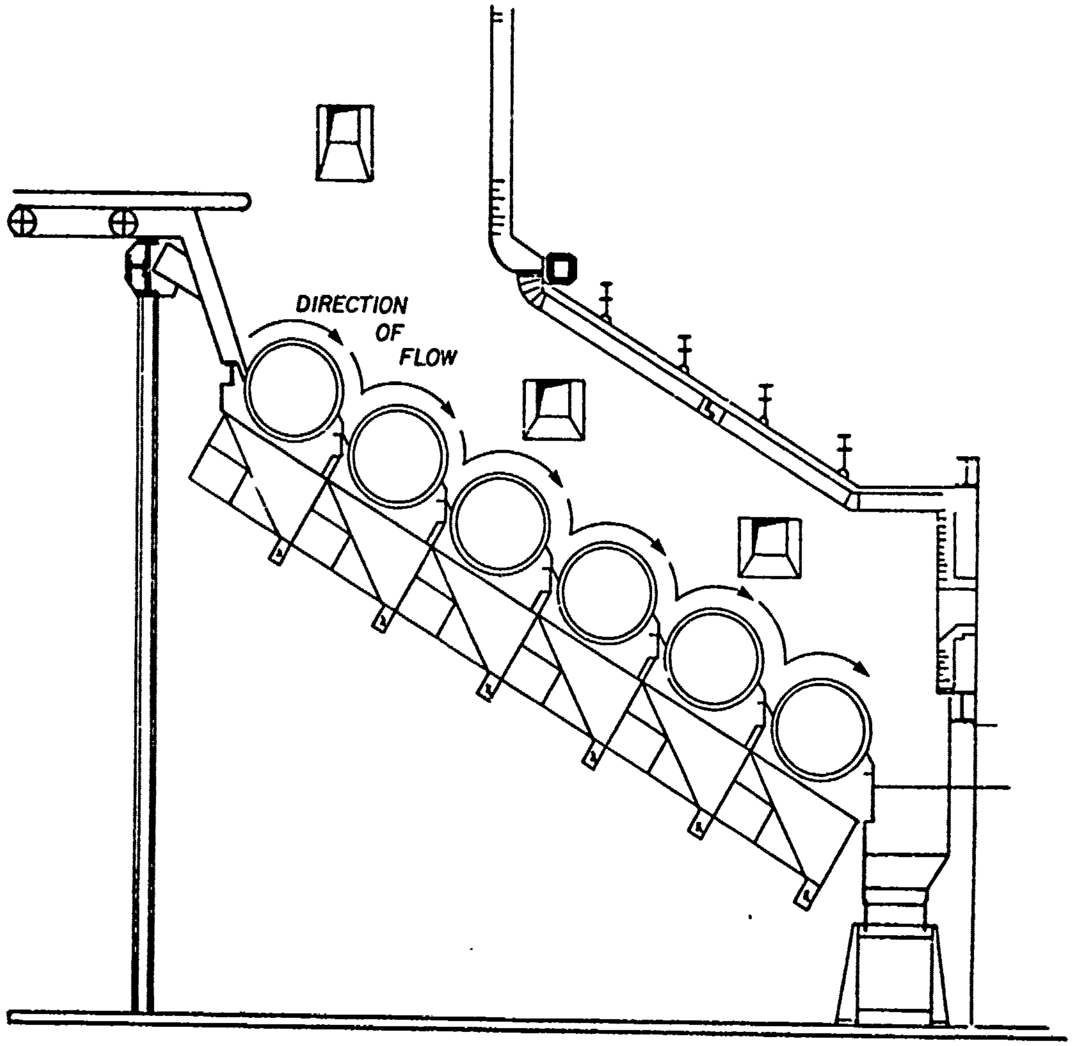


Figure 20. Rotary drum grate stoker.

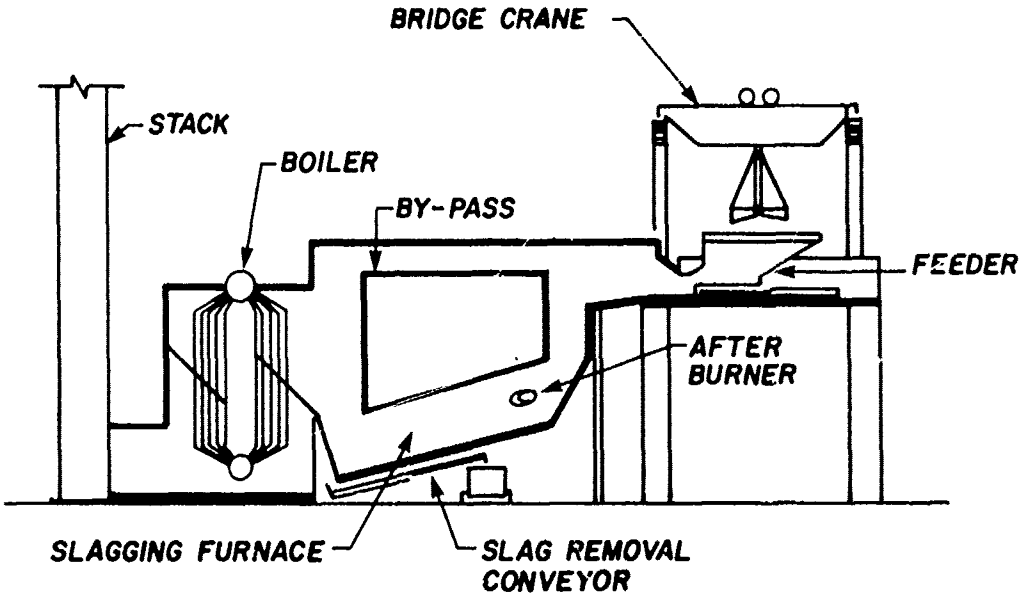


Figure 21. Reilly slag-forming incinerator.

undersized in comparison to conventional furnaces so that the existence of carbon monoxide in the presence of excess air is a distinct probability at the primary chamber exit. The extensive residence of the flue gas at high temperature levels in the slagging furnace and connecting passages assures the ultimate conversion of CO to CO_2. Such conversion would make additional heat available to the slagging furnace and further increase the estimated latitude of operation.

The processes for conveying the flue gas and slag residue following the slagging furnace are again conventional, tested procedures which are presently in use in operating plants. A rugged drag conveyor in the quench tank removes all of the solid residue from the process, including grate siftings, slag, and particulate from the flue gas. No further air cleaning requirement is anticipated.

The Reilly slag-forming incinerator uses "conventional" equipment and processes in waste incineration. A demonstration plant rated at 2 tons/hr (2 MT/hr) nominal capacity has been designed.

Current Technical Status

The successful operational history of field-erected mass burning systems warrants optimism regarding their potential application within the Army. This optimism must, however, be tempered by cognizance that functional aspects of proven large-scale systems may not necessarily extrapolate linearly to systems of the substantially smaller scale usable by the average installation. For large, regional systems based on waste generated by a group of jurisdictions or Federal agencies, me field-erected systems may find application.

Experience clearly shows that some waste preprocessing is required in order to achieve designed performance in combustion and energy-recovery. Coarse shredding is normally sufficient in cases where the waste stream contains an appreciable fraction of bulky combustibles.

Experience also points to the desirability of firing the waste via a mechanical stoking mechanism. The most favored is the double reciprocating grate, which was first used in 1970 and demonstrated excellent combustion efficiency with a wide range of refuse quality. This stoker has little tendency to foul and requires minimal maintenance. The simple reciprocating grate may also be recommended, although its performance characteristics are inferior to those of the double reciprocating grate. Even so, its application in smaller scale systems warrants consideration.

In general, stokers designed for European systems have little potential for Army use. In some cases, adaptation of some European stokers to U.S. municipal wastes has resulted in discouraging problems. U.S. waste is usually much drier and contains less wet garbage and more plastics and paper than European waste. In one CONUS application, a water spray is used to wet municipal waste before it is fed to an adapted European-type stoker. Such practice results in severe energy-recovery penalties.

While untried to date, the Reilly slag-forming incinerator warrants test and evaluation. Although its O&M costs may be higher than conventional field-erected systems (through added auxiliary fuel requirements and increased high-temperature wear on the refractory), substantial savings may be achieved if air pollution control hardware is not required. This unit's higher temperatures permit a greater heat exchange area than conventionally used. Additional potential advantages of the system are that it has few vital moving parts and was developed to process up to 3 tons/hr (2.7 MT/hr) the type of solid waste typically generated at small communities in CONUS.

Fluidized Bed Combustion

Fluidized bed technology has been commercial since 1942 when it was applied to catalytic cracking of crude oils. In concept, solid particles are set in fluidized motion in an inclosed space (fluidized bed zone) by forcing combustion air through the bed zone in such a manner as to set all particles into a homogeneous boiling motion. The particles are separated from each other by an envelope of the fluidizing medium and present an extended surface for gas-to-solid reactions. Mixing is achieved by dispersion of the fluidizing medium throughout the bed zone. The mass of the fluidized bed is maintained at combustion temperature by oxidation of the organic constituents of the feed. Combustion takes place at temperatures up to 1600°F in currently available fluidized bed waste-to-energy systems. To recover energy, package boilers are installed in the exhaust gas train of the fluidized bed system.

Systems currently marketed claim to accept unprocessed mixed solid waste with no operational difficulty. However, the concept is still in the developmental stage insofar as waste-to-energy systems are concerned, and no reasonably long-term records are available to substantiate these claims. At present, there is no fluidized bed waste-to-energy system in continuous full-scale operation in CONUS.

5 COMBUSTION SYSTEMS II: REFUSE-DERIVED FUELS

General

A refuse-derived fuel (RDF) results from any direct processing of solid waste into a material with improved physical and chemical properties. RDF is a general acronym used to refer to fuels produced from solid waste and destined for use in combustion systems.

Motivation for considering use of RDF may be purely technical or purely economic, but most often is a combination of both factors. A detailed investigation at a given site may show that it is more cost-effective to fire as-delivered solid waste in new energy-recovery capital. A similar study at another site may reveal that economic benefits are greater if solid waste is processed into a particular form of RDF and fired as a fuel in an existing steam generating system. RDF systems normally use central scale boiler plants, and the type of RDF to be processed and fired depends largely on the design characteristics of the candidate boiler.

RDF has several important advantages. First, by the nature of the processing lines, the output fuel's essential characteristics are normally less variable than those of as-delivered solid waste. This permits greater performance predictability and combustion control. Second, RDF systems use existing rather than new capital. It is currently thought that RDF can be used in substitution ratios (by lower heating value) as high as 20 percent with conventional fuels. A major disadvantage of RDF systems is that process rejects, which may be as great as 40 percent of the mass input to the processing line, remain as a waste disposal consideration.

This chapter describes the major types of RDF currently available. Considerations in using RDF in existing Army boilers are discussed in Appendix A.

Types of RDF

The four generic types of RDF are coarse, fluff, dust, and densified.

Coarse

Coarse I RDF is the lowest form of RDF. It is produced by primary ("coarse") shredding of delivered solid waste to an average particle top size of 6 in. (15 cm). The recommended size reduction apparatus is the top-fed, vertical, reversible drive hammermill with replaceable blade tips. Hammermills applicable to military wastes are normally procured with mass throughput capacities several times greater than required capacity. At the current state of the art, so-called "over-designed" shredders have feed entries large enough to accept most waste materials and have several times the durability of smaller units. The advantages of shredding include loosening the waste material; reducing waste materials to a smaller and more easily handled size range; increasing the surface-to-volume ratio and, hence, combustibilility of the waste; and, through mixing action, making the charge more homogeneous (less variable) than unprocessed solid waste. Shredding mass increases the ease and efficiency of thermal processing and lends stability to steam production performance in energy-recovery systems.

A second, more refined type of coarse RDF is producible. A coarse II RDF processing line may include an air classification stage after the shredder. In this step, heavier materials such as metals, large glass fragments, and injection-molded plastics are removed from the fuel with efficiencies ranging between 50 and 85 percent. The air classification stage is a technically advantageous addition in that it extracts from the fuel a fraction of those materials which are largely responsible for slagging (silicates, ferro-aluminum compounds) and cold-end corrosion (chlorides). The main shortcomings of the air classification stage are the passage of light metals (principally aluminum fragments), some rigid and film plastics, and glass particles which impregnate paper and cardboard during the shredding stage.

Approximately 20 percent of the delivered solid waste mass is rejected in a coarse II RDF processing line. Rejected wastes include ballistic rejects from the shredder, heavies from the air classifier, and dust and moisture losses. Rejects from the air classifier may pass through optional ferrous and aluminum separation stages for materials recovery.

Both types of coarse RDF have better combustion properties than as-delivered solid waste; many inerts and slag-forming materials are not present, and the lower heating value may be as much as 15 percent higher.

Installed capital costs of applicable hammermills range between $90,000 and $240,000. Because shredders are high-maintenance items (repairs, shutdowns, and manual removal of adverse materials such as cable, rugs, and bedding materials), an energy-recovery system using coarse RDF normally includes two shredders. Installed capital cost of zig-zag air classifiers ranges between $90,000 and $310,000, depending on capacity and structural support requirements.

Fluff and Dust

Fluff RDF is produced by subjecting coarse II RDF to subsequent screening and secondary (light) shredding stages (Figure 22). Screening normally is accomplished in a trommel screen which removes

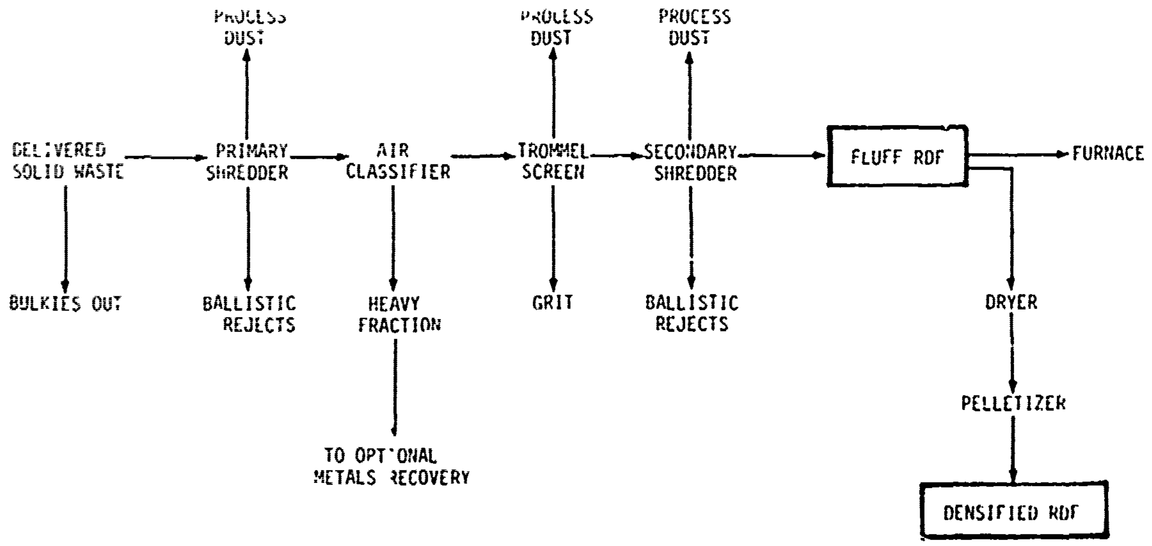


Figure 22. Process flow for production of fluff and densified RDF.

relatively minor masses of dirt and grit from the fuel. Secondary shredding normally is by relatively light-duty equipment. Due to removal of fines in the screening stage, fluff RDF has an ash content somewhat lower than that of coarse RDF. The lower heating value of fluff RDF can be up to 8 percent higher than that of coarse RDF. Tables 13 and 14 show proximate and ultimate analyses of fluff RDF.

Table 13

Proximate Analysis of Typical Fluff RDF

Constituent	Percent by Weight
Moisture	10.0
Volatile matter	40.5
Fixed carbon	38.0
Ash	11.5*
	100.0

*Can attain 23 percent if fines are not removed.

Table 14

Ultimate Analysis of Typical Fluff RDF

Constituent	Percent by Weight
Carbon	39.6
Hydrogen	5.3
Oxygen	32.3
Nitrogen	0.9
Ash	11.5*
Sulfur	0.1 - 0.2
Chlorine	0.1 - 0.2
Water	10.0
	100.0

*Can attain 23 percent if fines are not removed.

Fluff RDF has the technical advantage of being comparatively easily transported through pneumatic systems. However, this mode of transport is disadvantageous in that metals entrained in the light fraction may abrade hardware, causing sparks which can catalyze explosion or fire in the conveying system. Figure 23 shows fluff RDF produced at a commercial facility; materials such as a toothpaste tube cap, smashed ping-pong ball, and aluminum pull tab are clearly visible.

Dust RDF is manufactured by adding embrittling agents (usually a sodium-sulfur compound) and a pulverizing step to the fluff RDF process (Figure 24). Dust RDF consists largely of cellulosic material which is highly fibrous and nonhygroscopic, and has unique flow properties. The use of sodium-sulfur compounds as embrittling agents almost totally eliminates static fields from the fuel. While both types of coarse RDF are generally burned in combustors equipped with mechanical stokers, fluff and dust RDF are intended for suspension firing.

Tables 15 and 16 show proximate and ultimate analyses for dust RDF produced in CONUS Figure 25 is a general scale photograph of dust RDF. Figure 26 shows the highly fibrous nature of dust RDF. Fiber origin is mainly paper, wood, and textiles. Particles in Figure 25 are glass and grit.

Table 15

Proximate Analysis of Typical Dust RDF

Constituent	Percent by Weight
Moisture	3.59*
Volatile matter	64.84
Fixed carbon	15.59
Ash	16.01*

*Difference from ultimate analysis (Table 16) due to sample difference.

Table 16

Ultimate Analysis of Typical Dust RDF

Constituent	Percent by Weight
Carbon	46.19
Hydrogen	6.20
Oxygen	27.38
Nitrogen	1.03
Ash	16.77*
Sulfur	0.15
Chlorine	0.21
Water	2.07*
	100.0

*Difference from proximate analyses (Table 15) due to sample difference

Dust RDF is theoretically advantageous in that the fuel properties are more predictable than those of less-processed RDF types. The fuel is easily transported pneumatically. However, the flow properties of dust RDF are unknown. Moreover, as much as 40 percent of the waste mass delivered to a dust RDF processing line is rejected at various processing stages and must be disposed.

Production of fluff and dust RDF is capital-intensive. Producing fluff RDF from coarse RDF requires installation of a trommel screen ($15,000 to $48,000) and a secondary shredder ($60,000 to

Figure 23. Fluff RDF.

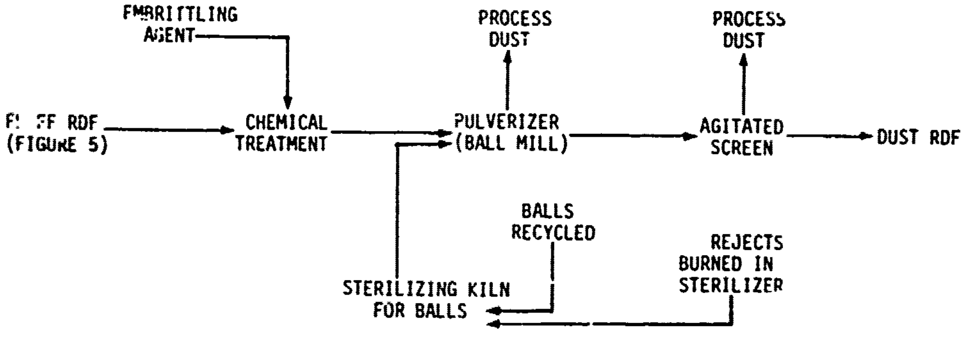


Figure 24. Process flow for production of dust RDF.

Figure 25. Dust RDF.

Figure 26. Microscopic photograph of dust RDF.

$150,000). A fluff RDF system also requires dust collectors for screening and shredding stages (unit cost $18,000 to $50,000), capability to handle ballistic rejects ($15,000 to $30,000), and an extensive material-conveying system ($40,000 to $200,000). Added capital to establish a dust RDF production line includes a heated chemical treatment system ($40,000 to $120,000), a pulverizer ($80,000 to $240,000), a sterilizing kiln ($95,000 to $210,000), an agitated screen ($10,000 to $25,000), dust collection equipment for the pulverizer and screen ($18,000 to $50,000), and material handling equipment ($45,000 to $100,000). The above costs apply only to systems having a capacity up to about 200 TPD$_s$ (181 MTPD$_s$). Capital costs increase, not necessarily linearly, for systems requiring greater throughput capacity.

Densified

Densified RDF can be produced either from fluff or dust RDF by adding a pelletizer after the product line, as shown in Figure 22. The particular nature of densified RDF depends on whether its parent material is fluff or dust RDF. The intent of producing densified RDF is to derive a fuel which can be handled in existing coal-handling systems at a particular site, and combusted in a steam generator equipped with a mechanical stoking mechanism. Figures 27 and 28 show scale photos of densified RDF produced from fluff and dust RDF, respectively.

The principal pelletizing method in current densified RDF production lines is mechanical extrusion, whereby a fluff RDF product is continuously delivered to a chamber and mechanically forced by moving rollers through a die around the chamber. Adjustable knives outside the die shear the extrudate to the desired pellet length. U.S. Army Construction Engineering Research Laboratory (CERL)[21] and other investigations of densified RDF production lines have indicated that a rotary dryer before the pelletizer may improve pellet quality.

Capital required for pelletizing capability includes a rotary dryer ($80,000 to $195,000), a pelletizer ($80,000 to $120,000), and material-moving capability which may include a vibrating feed hopper to the pelletizer ($20,000 to $65,000).

Current Technical Status

Numerous coarse RDF lines are currently operational.[22] Some lines have only a shredder, while others add an air classifier. Only a few fluff RDF lines are currently operational; those have been so for only a few years. The production of dust RDF is currently developmental.[23] No DRDF production system has been commercial for more than 2 years.[24]

Technical problems of the various RDF production lines focus on shredders, classifiers, screening stages, and material-moving operations.

Shredders are subject to severe wear and unexpected downtime.[25] Relatively high maintenance costs are required for frequent hammer tip repair (usually welding) or replacement. Presence of cables, rugs, large pieces of cardboard, and kindred materials in the waste tend to foul shredders, requiring that they be brought off-line and the materials manually removed. In civilian systems, explosions have resulted from highly volatile materials being fed to the shredder. Glass and ceramic fragments impregnate paper, cardboard, and wood, rendering their removal in subsequent RDF processing stages virtually impossible.

Air classifiers generally fail to remove light metal fragments and film plastics from the potential fuel fraction. Metals, glass, and grit can bring about severe erosion problems in pneumatic systems. The presence of metals and film plastics in densified RDF is highly undesirable, since pellets readily break at interfaces of the cellulosic fraction and such materials. The presence of metals in pelletizer feed can result in plugging and excess wear of dyes and increased unit downtime.

Trommel screens are installed in RDF processing lines to remove inert fines from the fuel fraction. Removal efficiencies are often relatively low, however. Attempts are currently being made to evaluate the impact of detention time and rotational speed on the removal efficiency for fine materials. To date,

---

[21] S. A. Hathaway, J. S. Lin, A. N. Collishaw, *Design Concept for Densified RDF Production and Handling Systems in Military-Scale Applications*, Draft Technical Report (CERL, 1977).

[22] H. Schutz, "Energy from Municipal Refuse: A Comparison of Ten Processes," *Professional Engineer* (March 1976).

[23] *Combustion Performance Tests of Ecofuel II at Weyerhauser Company, Fitchburg, Mass.* (York Research Corporation, 1974).

[24] *Solid Waste Fuel Modifications, Second Series, Burn Tests—Final Report* (Eugene Water and Electric Board, 1974).

[25] G. Savage and G. Trezek, "On Grinder Wear in Refuse Comminution," *Compost Science* (September-October 1974).

Figure 27. Densified fluff RDF.

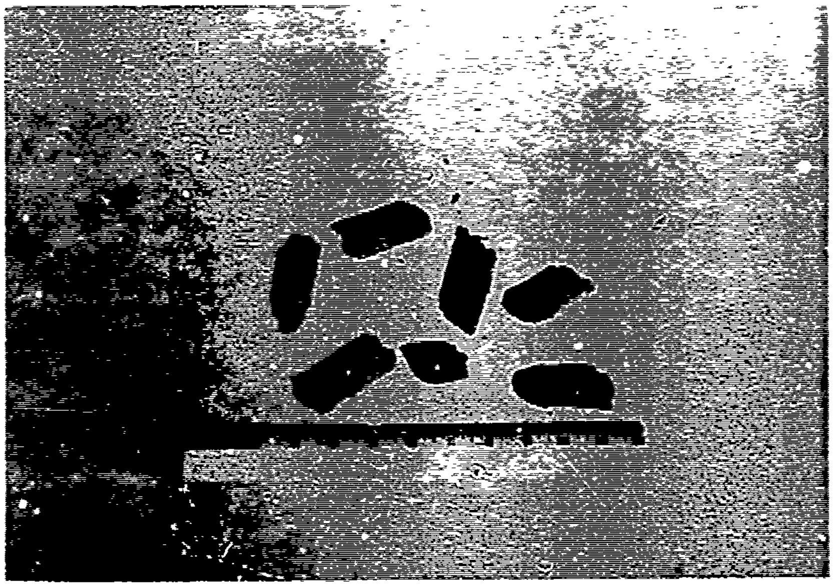


Figure 28. Densified dust RDF.

no comprehensive data exist by which to evaluate the performance of trommel screens in RDF production lines.

Field observations of RDF production lines have revealed two major technical problems associated with material-moving systems. Numerous configurations of belt conveyors show a pronounced tendency to foul from spillage of the product. Dust generation is also a problem, but is not limited to transport operations. Shredders and agitated screens generate substantial quantities of process dust during routine operation. Dust collectors required for safe process plant operation are a necessary but frequently overlooked capital item.

Package RDF Systems

Operation

Package combustion heat-exchange systems for the firing of RDF are essentially the same as those reviewed earlier for mass-burning solid waste. Performance characteristics of package systems generally improve with the degree of waste preprocessing, which yields a charge of less variable particle size and one from which many potential slag-forming materials have been removed. A typical package RDF system would fire a coarse (shredded and possibly air-classified) RDF produced in a small processing line located on-site.

Current Technical Status

The critical analysis of package mass-burning technologies also applies to the current technical status of package RDF systems. However, unlike mass-burning package waste-to-energy systems, no package RDF system has been operating for any appreciable length of time. Further test and evaluation is required to determine if package combustion heat-exchange systems show improved performance characteristics when burning coarse RDF as opposed to as-delivered solid waste.

Field-Erected RDF Systems (New)

Operation

New systems are those for which completely new combustion-heat-exchange hardware designed specifically to fire a form of RDF—either purchased from a supplier or manufactured in an on-site processing line—is installed. Nearly all new field-erected RDF systems currently in operation fire coarse RDF by mechanical stoking mechanism in a waterwall combustor.

Many of the stoking mechanisms and furnace configurations which may apply in firing coarse RDF in new field-erected systems are reviewed in the section on mass burning. Installation of new total process capital to fire forms of RDF more refined than coarse is generally counterproductive to the central objective of producing RDF, i.e., deriving a suitable fuel for supplementary use in existing steam generating equipment.

Currently operating new field-erected RDF systems in North America fire a coarse RDF manufactured by primary shredding of delivered municipal waste. These systems are located in Harrisburg, PA; Hamilton, Ontario; and Montreal, Quebec. The Hamilton system incorporates magnetic separators for ferrous metals recovery between the shredder and the furnace. The systems are designed to process 720, 600, and 1200 tons/day (653, 544, and 1088 MT/day), respectively.[24]

Current Technical Status

No new field-erected RDF system has been operational for more than 4 years in North America. In Europe, it is becoming common practice to shred solid waste into coarse RDF before feeding it to the combustor in order to improve system performance. No new field-erected fluff, dust, or densified RDF systems are currently continuously operated. There is no reasonably long-term, comprehensive set of operating data on new field-erected RDF systems by which to comprehensively evaluate the performance of currently operating systems or to guarantee adequate operation of those which might be constructed in the near future. While current systems integrate combustion-heat-exchange equipment which has an established history in coal utilization, it is not known what the precise performance characteristics will be when such concepts are scaled down to the level of processing required by a typical Army installation. Further test and evaluation of such systems is required prior to their implementation as a sound waste disposal energy-recovery measure.

---

[24] R. Schwieger, "Power from Waste," *Power* (February 1975); and H. Schutz, "Energy from Municipal Refuse: A Comparison of Ten Processes," *Professional Engineer* (March 1976).

Use of RDF in Existing Steam Generators

General

Use of RDF in existing steam generators has drawn widespread attention ever since Union Electric Company began firing coarse (shredded, air-classified) RDF as a supplementary fuel with pulverized coal at the Merimac Plant in St. Louis in 1972.[27] The central consideration involves boiler modification and fuel substitution. The magnitude of current interest in this subject and the technical detail involved warranted an extensive investigation into this aspect of energy recovery. Appendix A summarizes this investigation. Current technologies are discussed below.

Operation

Coarse II RDF is currently suspension-fired with pulverized coal in St. Louis. Coarse RDF is tangentially fired through cornerwall burners adjacent to the coal burners. The project involves using two existing pulverized coal-fired boilers rated at 925,000 lb/hr (419 571 kg/hr) to produce high-pressure steam for electric power generation.

A fluff RDF plant is planned for firing in the Ames, IA, solid waste recovery system.[28] Although the planned startup date was June 1975, the system is not yet fully operational. The plant consists of two (primary and secondary) shredding stages, a magnetic removal system for ferrous recovery, and an air classifier. The main combustor is a modified 380,000 lb/hr (172 365 kg/hr) high pressure steam boiler; fluff RDF will be cofired with pulverized coal in the same manner as at the St. Louis plant. Two spreader-stoker equipped boilers (125,000 and 95,000 lb/hr [56 699 and 43 091 kg/hr]) serve as backup.

No system firing dust RDF is currently operational. Current experimentation is focusing on designing systems to improve fuel properties and on mixing the fuel with fuel oil and firing the slurry. Current thinking is that dust RDF can be fired in much the same manner as pulverized coal.[29]

Use of densified RDF as a supplementary fuel has been tested with varying degrees of success. Eugene Water and Electric Board, OR, tested densified RDF (parent: fluff) in a 150,000 lb/hr (68 039 kg/hr) high pressure steam boiler in 1974 with minor success. The Eugene test resulted in the following conclusions.[30] For fuel handling, a separate receiving and handling system is required, dust and housekeeping problems are created, and fire and health hazards must be guarded against. For combustion aspects, complete modification of conventional firing methods is necessary; corrosion, erosion, and pluggage problems can be anticipated in long-term use of RDF. Burning RDF results in emission of very small particulate matter, requiring modification of air pollution control equipment if existing standards are to be met. No known experimentation has been conducted with dust-parent densified RDF.

Current Technical Status

No RDF system of the type reviewed in this section is commercial. Systems currently operating are municipal and are considered to be developmental or demonstrative. Appendix A contains a detailed critical technical treatment of use of RDF as a supplementary fuel in Army-scale central steam generators. At the current state of the art, installation use of RDF as a supplementary fuel in existing boilers would include experimental and developmental aspects.

Fluidized Bed Combustion Systems

Operation

The concept of fluidized bed combustion is discussed in Chapter 4. A fluidized bed waste-to-energy system using coarse RDF is currently under development by Combustion Power Company (Menlo Park, CA) under funding by the U.S. Environmental Protection Agency.[31] The light fraction of mixed solid waste is combusted in the reactor, and off-gases pass through a gas turbine electrical generator set. The reactor is made of carbon steel lined with refractory brick and ceramic-fiber insulation. Sand is used as the fluidizing medium. Operating temperatures range between 1500°F and

---

[27] R. Schwieger; H. Schutz.

[28] R. Schwieger; H. Schutz.

[29] *Combustion Performance Tests of Ecofuel II at Weyerhauser Company, Fitchburg, Mass.* (York Research Corporation, 1974).

[30] *Solid Waste Fuel Modifications, Second Series Burn Tests—Final Report* (Eugene Water and Electric Board, 1974).

[31] *Fuels from Municipal Refuse for Utilities: Technology Assessment* (Bechtel Corporation, March 1975).

1800°F (807° and 972°C). Three stages of dry cyclonic separations clean the gas before the turbine. The first stage is integrated into a sand separator which removes entrained fluid bed material and "plastic" particulate (glass, ferro-aluminum compounds).

The demonstration plant has had little success. Performance of gas-cleaning equipment has been very poor, resulting in low turbine efficiency and a high wear rate. Vendors claim that such a plant processing 1000 tons/day (907 MT/day) will generate 31 MW electricity (133 psig). The pilot plant processing 80 tons/day (73 MT/day), however, has not consistently produced more than 1 MW.

Fluidized bed waste-to-energy systems firing forms of RDF other than coarse do not exist.

Current Technical Status

Fluidized bed waste-to-energy systems firing RDF are limited to the facility described above. No long-term data exist by which to predict or guarantee performance of such systems. Any application of fluidized bed technology using RDF would be highly developmental and not a proven measure for waste disposal or energy conservation efforts.

6 PYROLYTIC CONVERSION OF WASTE TO ENERGY

General

The basic chemical processes in the pyrolytic conversion of waste to energy are detailed in Chapter 3. Nearly all developing pyrolysis systems aim at producing a low-grade gaseous fuel which can have a lower heating value up to 30 percent of that of natural gas and can either be fired on-site as a supplementary fuel or temporarily stored and transported by conventional modes to a user. An advantage of pyrolysis is the separation of the fuel volatilization (pyrolytic distillation) and actual oxidation (combustion) processes, which in energy-recovery incineration and RDF systems occur in the same vessel. It is felt that greater control of the total energy-recovery process can be achieved by dealing with unpredictably variable volatilization rates in a separate process, and feeding the more homogeneous, cleaner fuel to the combustor. A disadvantage of pyrolytic processes is their lower waste-to-stream efficiency. A penalty is paid in not fully using the fixed carbon, which remains in the solid char in the pyrolysis reactor; the fixed carbon usually undergoes only incomplete oxidation to liberate heat to drive the distillation process.

The technical potential of employing pyrolysis to yield a gaseous RDF for use as a supplementary fuel in an existing small-scale boiler is addressed in Appendix A. This chapter considers current pyrolytic conversion systems in terms of their general operational characteristics and current technical status.

Basic Process Flow

Numerous pyrolytic conversion systems are currently under development (Appendix B). While each system is unique, they all share a common general process flow. Mixed solid waste is delivered to the pyrolysis facility and processed (either as-delivered or after refining stages) in a reactor vessel under high temperatures and less than theoretical air. The main products are energy-rich off-gases which can be used as fuel and a nonputrescible residue or char.

Torrax System[32]

The Torrax process (Figure 29) was developed by Carborundum Environmental Systems, Inc., and is now undergoing demonstration in a pilot plant in Erie County, NY, under joint sponsorship of Erie County, the American Gas Association, the U.S. Environmental Protection Agency, and the New York State Department of Conservation. Delivered waste is moved by grapple into the inlet hopper of the reactor vessel. In the vessel, the material moves by gravity through drying, pyrolysis, and primary combustion zones. A molten slag is tapped and fritted to a black glassy aggregate free of putrescible material and most carbon. Primary air is introduced at 2000°F (1100°C) through the bottom of the vessel. Pyrolysis gases exit the vessel at temperatures up to 1000°F (538°C) and are mixed with minimum (15 percent) excess air in a secondary chamber where combustion takes place at up to 2300°F (1260°C). Two regenerative towers recover heat from the combustion products to heat primary combustion air. About 85 percent of the gaseous combustion products pass through a waste heat boiler for steam production, and then join gases passing

---

[32] *Final Report for Erie County-Torrax Solid Waste Demonstration Project* (Carborundum Environmental Systems, Inc., Torrax Division, May 1974).

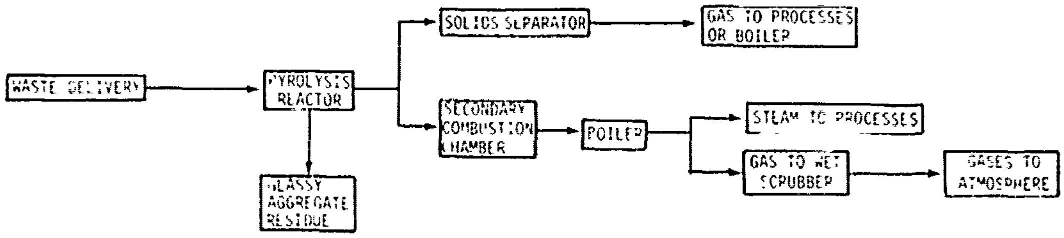


Figure 29. Torrax pyrolysis system.

from the regenerative towers before air pollution control apparatus. The plant has a nominal capacity of about 300 tons/day (272 MT/day) and produces up to 6000 lb/hr of steam per ton of waste (3000 kg/MT).

Purox System[33]

Like the Torrax system, the Purox process (developed by Union Carbide) uses unprocessed solid waste (Figure 30). Delivered material is fed to the top of a vertical shaft furnace. Oxygen injected into the bottom reacts with the hot char, liberating heat to drive the pyrolytic reactions. Slag is quenched, developing into frits. Gases exit the reactor and pass through a precipitator-condenser system to strip water vapor, oil mist, and other undesirable constituents. A minor quantity of the fuel gas is used to generate process steam and building heat, and to provide energy required to keep the auxiliary combustion chamber at adequate operating temperatures. A small pilot plant has operated for several years in Charleston, WV.

Garrett (Occidental) Process[34]

Figure 31 is a simplified process flow diagram of the Garrett Research and Development Co. (now Occidental Research Corp.) pyrolysis process, which employs an extensive waste preprocessing line, consisting of a primary shredder, air classifier, dryer, agitated screen, and secondary mill. Steps to recover ferrous metals, glass, and aluminum are integrated into the process. The objective of the preprocessing stages is to provide a fine, inorganic-free feed to the flash reactor. In the reactor, the feed is rapidly heated to 900°F (477°C) using recycled hot char. The gaseous fuel and a portion of the char are used on-site for process heat. Details of reactor design and the precise method employed for heating the feed are proprietary and have not been disclosed. The product of the system is a fuel oil which may be fired in utility boilers. About 1 barrel/ton (0.18 m^3/MT) of delivered waste is expected to be produced at a 200 ton/day (181 MT/day) pilot plant in San Diego County, CA. The San Diego Gas and Electric Company plans to test and use the pyrolytic oil in one of its power generating stations when the pilot plant goes on-line in early 1977.

Monsanto-Landgard Process[35]

Figure 32 shows the process flow for the Monsanto-Landgard process. Delivered waste is shredded and moved to temporary storage in a 2000-ton (1814 MT) capacity surge bin. The material is ram-fed to a rotary kiln to which auxiliary fuel and oxygen are introduced at the opposite end. Pyrolytic reaction takes place at 1800°F (982°C) to form gases, oils, and char. Incombustibles and char pass to a quench, after which a magnetic separator removes ferrous metals. Gases exit at 1000°F (538°C), pass through an afterburner, and are combusted on-site in a waste heat boiler rated to produce 200,000 lb/hr (90 718 kg/hr) 330 psig saturated steam. A demonstration plant is jointly funded by the U.S. Environmental Protection Agency, the State of Maryland, and the City of Baltimore; its cost is estimated to be $16 million, and it is expected to go on line in 1977.

Other Pyrolysis Systems[36]

Process flows for other pyrolysis systems are shown in Figures 33 through 35. These systems generally follow the same principles as the four major developing processes. Plasma torch pyrolysis, however, is an exception; its concept is to employ high voltage electricity to heat raw waste in the

---

[33] *Fuels from Municipal Refuse for Utilities: Technology Assessment* (Bechtel Corporation, March 1975).

[34] F. P. Linaweaver, "Baltimore to Use Pyrolysis for Refuse Disposal," *Public Works Magazine* (March 1974).

[35] *Fuels from Municipal Refuse for Utilities: Technology Assessment* (Bechtel Corporation, March 1975)

[36] *Fuels from Municipal Refuse for Utilities.*

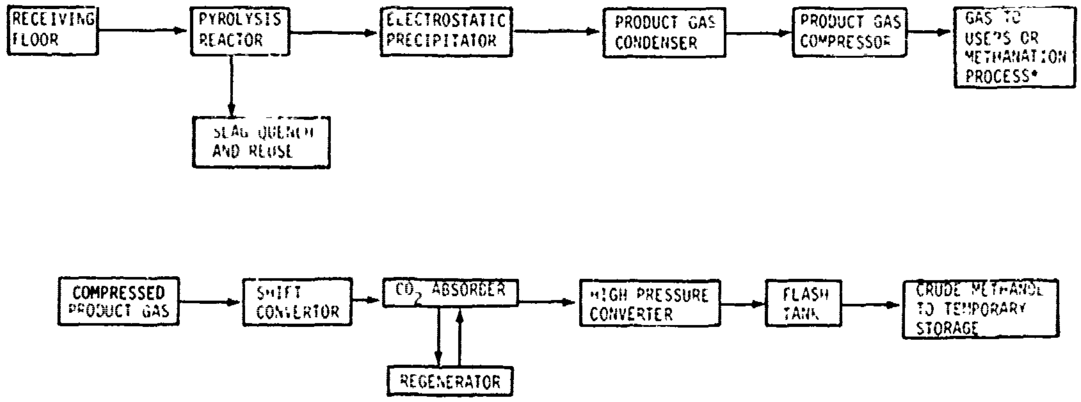


Figure 30. Purox pyrolysis system.

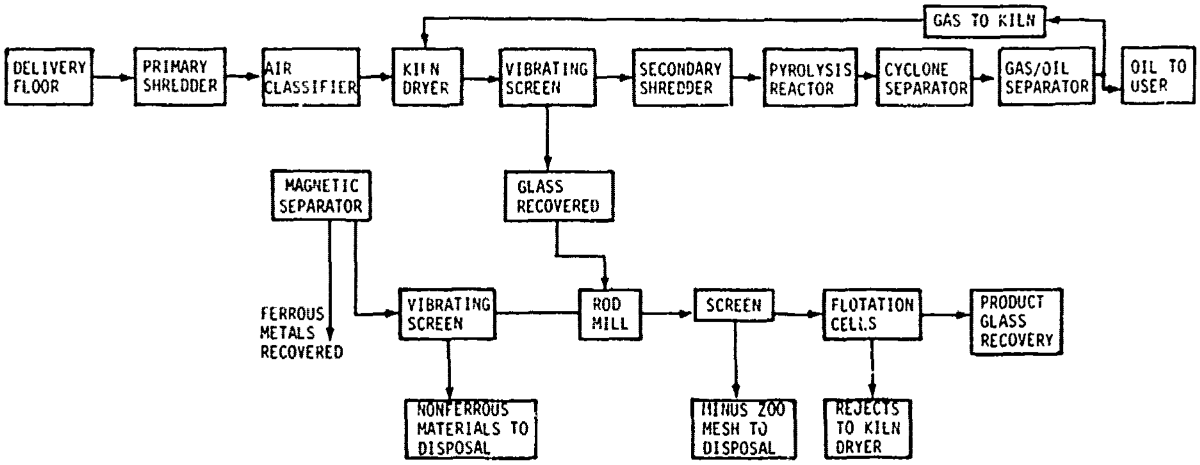


Figure 31. Garrett (Occidental) pyrolysis system.

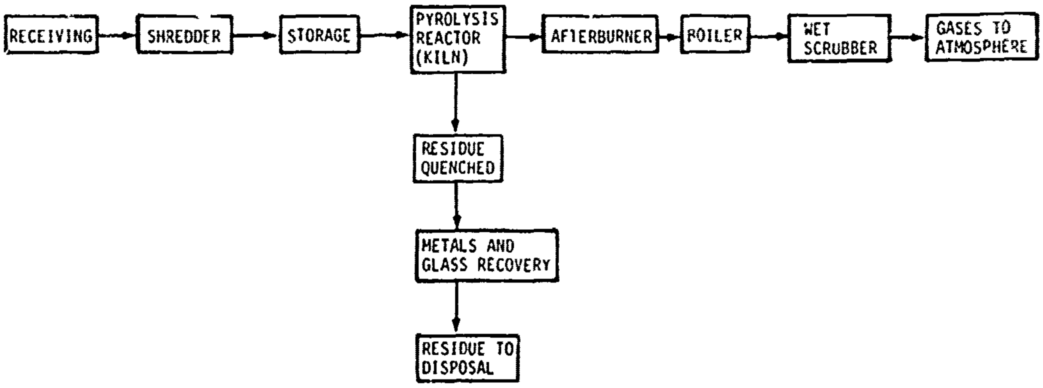


Figure 32. Monsanto-Landgard pyrolysis system.

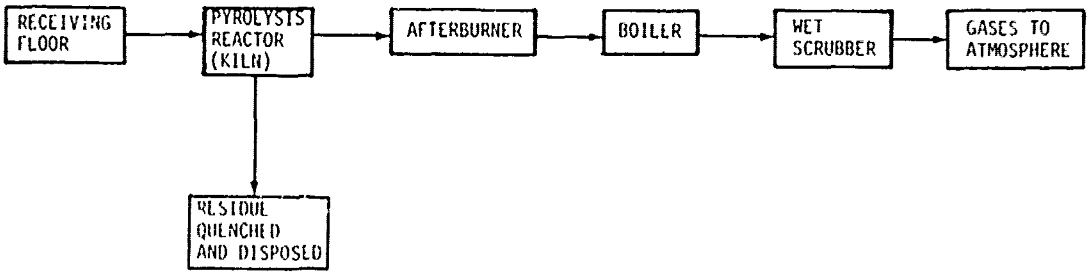


Figure 33. Devco management pyrolysis system.

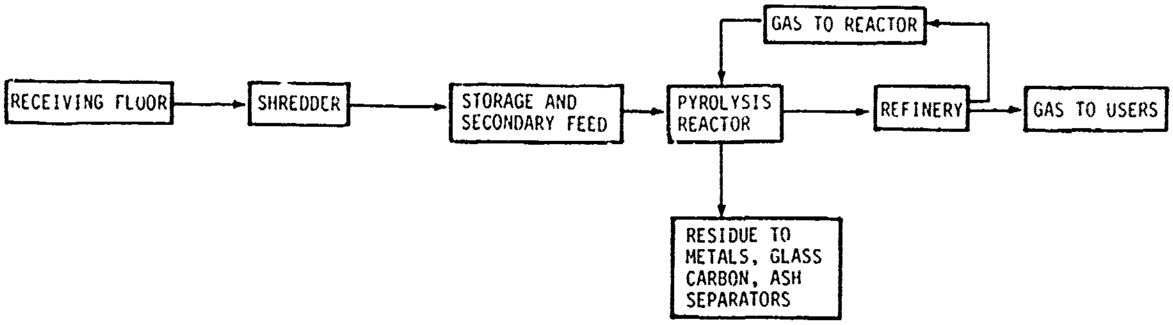


Figure 34. Resource sciences pyrolysis system.

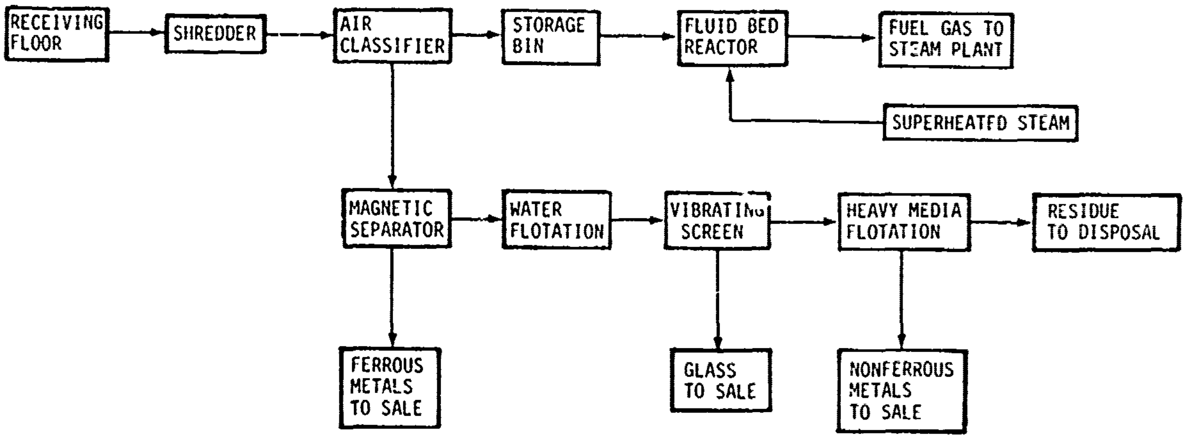


Figure 35. Coors pyrolysis system.

pyrolysis reactor vessel. Energy-rich off-gases are intended for use as fuel. A by-product is slag frits which can be recycled in road pavings or kindred applications. No plant has been built using the plasma torch pyrolysis principle, and little system information is available.

Current Technical Status

With the exception of the Coors plant in Golden, CO (Figure 35), all planned and operating pyrolysis plants are pilot or demonstration projects. The Coors system has had virtually trouble-free operation for several years, processing about 24 tons/day (22 MT/day) of waste. No other plant has as long an operating history.

Numerous technical questions must be satisfactorily answered before pyrolysis can find reasonably guaranteed application as a reliable waste disposal/ energy conservation measure. The long-term effects of high temperatures on vessel material are of concern. Some existing demonstration plants have suffered cracking of the reactor vessel after relatively short line time.[37] Moreover, in nearly all current plants, gravity is the major force driving flow of the waste through the vessel. Waste tends to resist free flow and can severely swell or cake in such processes. Severe agglomeration can inevitably lead to process cessation. Vendors of pyrolysis systems provide little technical information on this point. Further test and evaluation are required to obtain sufficient data to ascertain long-term potential of pyrolysis systems with a reasonable degree of confidence.

7 ANAEROBIC DIGESTION

General

In the absence of oxygen, organic matter decomposes by a process known as anaerobic digestion. The products of this process are methane and carbon dioxide. While the overall thermal efficiency of this process is low, the production of a high-quality fuel from refuse and sewage sludge has aroused considerable interest. Two major problems with the process are excessive time required to obtain reasonable efficiency and the need for careful regulation of process conditions to avoid poor operation or even total process breakdown. Large initial capital investments are required for landfill methane recovery and controlled digestion operations.

Anaerobic digestion is basically a two-stage process. The first stage consists of the conversion of complex organic compounds to short chain organic acids by anaerobic bacteria. Carbon dioxide is liberated as these fats, proteins, and carbohydrates are decomposed, and ammonia is formed by the deammination of biodegradable proteins. A portion of the carbon dioxide dissolves in the water while the remainder escapes with the methane produced in the second step. In this step, methane bacteria convert the organic acids to carbon dioxide and methane. Since methane is not water-soluble to any appreciable extent, it all escapes with the undissolved carbon dioxide.

Different bacteria act on specific compounds. The most important, those which break down acetic and propionic acids, grow very slowly and are rate-limiting at normal temperatures (80 to 120°F [27° to 49°C]) and retention periods (under 10 days). Carbon dioxide is enzymatically reduced to methane by hydrogen atoms from organic compounds. At the completion of this step, the waste material has been stabilized.

Several conditions must be met for the anaerobic digestion to proceed satisfactorily. The reaction temperature is an important parameter in determining reaction rate. While high temperatures produce fast reactions, the use of methane to heat controlled digestion slurries to a high temperature is costly and usually uneconomical. A higher concentration of waste will also speed reactions. The reaction environment must be free from oxygen and supply nitrogen and phosphorus as well as small amounts of sodium, potassium, calcium, magnesium, and iron. Freedom from toxins such as sulfides, heavy metals, and toxic organic compounds is also necessary. These are often present in refuse and must be either removed or inactivated. The pH should be between 6.6 and 7.6; the optimum value is between 7.0 and 7.2. Due to caustic reactions of carbon dioxide to form bicarbonate ion, the pH tends to drop and an alkali must be added. Both lime and sodium bicarbonate are commonly used.

Methane Recovery From Landfills[38]

Operation

At depths greater than 20 ft (6 m), a landfill becomes essentially anaerobic. Bacterial decomposition produces methane and carbon dioxide in approximately a 55:45 volumetric ratio. Gas production in such landfills is expected to last as long as 10 years. A pipe is sunk into the landfill to a depth of 40 to 100 ft (12 to 30 m) and induction blowers are used to remove the gas (Figure 36). This equipment must be capable of handling the acidity of the raw gas. Gases can either be used directly in a raw-gas-firing system or can be routed through a gas cleanup stage. If the gas is cleaned, carbon dioxide is removed by molecular sieves, amine solutions, or hot potassium solutions, and water vapor is removed in a condenser. The remaining gas is almost pure methane and can be used or sold commercially.

---

[37] J. Moore, "More Cities Find New Disposal Systems Fail to Meet Cost and Performance Goals," *Wall Street Journal* (21 July 1976), p 28.

[38] *Fuels from Municipal Refuse for Utilities: Technology Assessment* (Bechtel Corporation, March 1975).

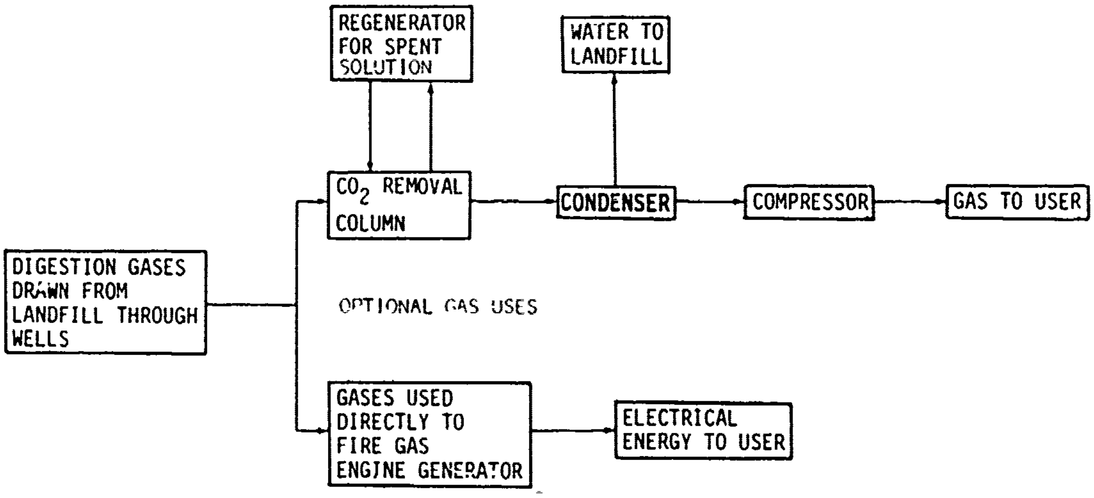


Figure 36. Recovery of methane from landfill.

Current Technical Status

The recovery of methane from landfills has several benefits other than the production of a valuable fuel. Gas odor usually present at landfill sites is eliminated, as are problems of gas migration to adjacent areas. Potential leachate problems are also diminished. Problems with this method of energy recovery include low energy yields, high capital costs, and the sensitivity of bacteria to their environment. Currently, the Los Angeles Water and Power Company is operating a gas-engine electrical generator set run by raw gas recovered from landfill, but it has not been in operation long enough to allow conclusions as to technical and economic feasibility. At present, there is no evidence that landfill methane recovery is reliable or economical.

Controlled Anaerobic Digestion[39]

Operation

In this method of methane production, processed refuse and raw sewage sludge are digested by bacteria in the controlled environment of a closed fermentor (Figure 37). Carbon dioxide and water vapor are removed from the gas produced; the result is almost pure methane. Since the gasification process is inefficient, incineration of digester residue is used to liberate additional heat and to effect further volume reduction. Raw refuse is processed by shredding, magnetic separation, trommel screening, and air separation to remove most inert matter from the organics. The organic matter is mixed with sewage sludge in a blending tank and fed to the fermentor, where the retention period ranges from 5 to 15 days. Gas is upgraded in the same process used in the landfill recovery method and used on-site or sold. The digester residue is dewatered by centrifuge or vacuum filter and incinerated. Waste heat recovery at this point may be economical.

Current Techncial Status

While this process's overall thermal efficiency and volume reduction are better than those of landfill methane recovery, initial capital outlays are extremely large. Extensive research, including computer modeling to determine optimum economic operation, done by Pfeffer at the University of Illinois has resulted in favorable conclusions. However, no pilot plant has been built, and the process remains unproven to date.

8 COMPARATIVE RATINGS OF WASTE-TO-ENERGY SYSTEMS

General

The comparative rating system applied in this investigation was adapted from one developed to evaluate competing waste-to-energy alternatives at

---

[39] John T. Pfeffer, *Reclamation of Energy From Organic Refuse: Anaerobic Digestion Process*, presented at the Third National Congress on Waste Management Technology and Resource Recovery, San Francisco, CA (14-15 November 1974).

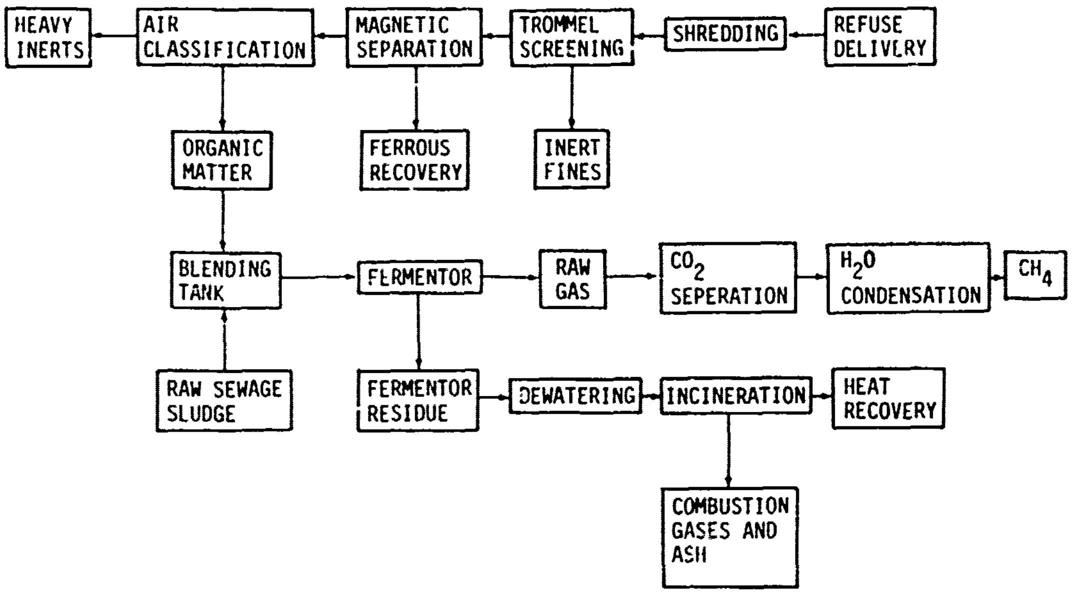


Figure 37. Controlled anaerobic digestion process.

a particular site.[40] Information used in the rating system was derived from manufacturers and vendors, field observation, a literature review, and past and on-going CERL studies of energy-recovery feasibility at various military installations. In adapting the system to meet the general requirements of this investigation, numerous assumptions were made regarding waste generation rate and characteristics and plant capacity. The comparisons are presented only as a general indication of the technical status of waste-to-energy technologies rather than a rigorously precise relative determination. The feasibility of applying a particular proven technology at a given location can be determined only through detailed and comprehensive study, with careful consideration of site-specific characteristics and requirements.

Comparative Rating Criteria

Like other acceptable technologies, a waste-to-energy system must be dependable, operationally practicable, conservative, environmentally compatible, reasonably economic, and must have an adequate operational history by which to responsibly predict and guarantee its performance.

Dependability includes reliability and is a measure of the degree to which a design follows a proven art and the potential of the designed system to withstand predictable wear over a specified period of time (the system economic or functional life, which in economic analyses is usually assumed to be between 20 and 30 years).

Practicability refers to the degree of a system's complexity which would make proper performance contingent on highly skilled personnel. It is related to ease and intensity of day-to-day operation, preventive routine and cyclic maintenance requirements, and procurement and installation of replacement parts.

Conservation refers to the degree to which a system reuses or recaptures energy and materials, or the extent to which a system consumes those resources supplied by external sources. It is a measure of system efficiency.

Environmental compatibility is measured by the impact of system operation on the immediate air, water, and land environments.

Operational history is measurable in terms of the combined use of similar equipment in a system for converting waste to energy. Operational history forms the critical basis for predicting and guaranteeing the life-cycle performance of a system with reasonable accuracy.

Economy is directly measurable in terms of first cost (including capital investment and first-year

---

[40] *Refuse Incinerator/Heat Reclamation Boiler Facility, Naval Station Mayport FL* (Greenleaf/Telesca, Planners, Engineers, Architects, Inc., 1975).

expenses such as startup) and recurring costs (annual and cyclic operation and maintenance costs).

Package Waste-to-Energy Combustion Systems

Table 17 summarizes the comparative ratings for package waste-to-energy systems. The ratings generally apply both to package mass-burning and coarse RDF systems, although minor differences in the ratings are revealed if each is considered separately. In the ratings in Table 17, each system was given a score in each category ranging between 1 and 4 (1 being best), so that each row item summed to 10 points. The best possible total score is 15 (a score of 1 for each item), and the worst is 60 (a score of 4 for each item). The percentile score (based on 15 = 100 percent and 60 = 0 percent) and percentile score range (based on the standard deviation) indicate that the starved-air system, while not absolutely superior, is the relative best among the package systems, with the augered-bed incinerator rated second.

Field-Erected Waste-to-Energy Combustion Systems

Table 18 gives the comparative ratings of field-erected waste-to-energy systems using combustion as the basic conversion process. Two broad categories of systems were considered: combustion in new capital and use of RDF in existing, modified steam generating hardware. Both types of coarse RDF were considered for application of the rating system. Scores assigned to each category ranged from 1 to 4, with each row item summing to 15. The best possible column total is 15, and the worst is 60. The percentile scores and percentile score ranges indicate the relative superiority of mass-burning and coarse RDF I systems. Mass-burning and use of coarse shredded RDF in new combustion capital are considered satisfactory for installation application. Use of coarse RDF achieved an average item score of 2.17 (61 percentile, ranging to 92), while the average item score of mass burning was found to be 2.27 (58 percentile, ranging to 90).

The Reilly slag-forming incinerator and fluidized-bed combustion were omitted from the evaluation because of the paucity of test information available. Judgments based on experience suggest that the Reilly incinerator may be rated competitively with mass-burning, and that its performance will improve somewhat with preprocessing of the waste into a coarse RDF I. The great number of unpredictable factors involved made fluidized-bed combustion impossible to rate confidently and accurately. This system's application to waste processing is still in early developmental stages.

Pyrolytic Conversion Systems

Table 19 presents the comparative ratings of pyrolytic conversion systems. Of the numerous pyrolysis systems described earlier, only four were rated; information on the remaining systems was incomplete. The ratings were derived in the same manner as those for package systems; they show that the four systems considered, which are the most developed pyrolysis systems, rank very close to each other. The highest percentile score is 58 (Torrax process); however, the upper limit of all percentile score ranges never exceeds 66 (Torrax process).

9 CONCLUSIONS

A major factor affecting the potential use of installation mixed solid waste as an energy resource is its variability. At a given installation, the daily generation rate, constituency, and condition of solid waste change over time. Correspondingly, the total waste stream energy potential varies continuously within usually wide boundaries. Currently practiced methods of determining critical design parameters for Army-scale waste-to-energy systems do not satisfactorily account for the dynamic characteristics of the waste stream. At present, no proven protocol has been demonstrated for surveying installation solid waste for accurate design of an energy-recovery system. Historical records of installation waste generation rates are usually on a volumetric basis and are of minor use in design, since bulk density of the waste is highly variable. Current practices of assuming a constant density to convert from volume to weight data for recovery program development are highly questionable, because they ignore both the time-variability of installation waste characteristics and the great differences in the nature of the waste from place to place.

Of the four major currently marketed modular incinerators of potential use in package waste-to-energy systems, the augered bed, basket grate, and rotary kiln are virtually unproven and require further development, test, and evaluation before they can be guaranteed to operate reliably for a reason-

Table 17

Comparative Ratings of Package Waste-to-Energy Combustion Systems

	Starved Air	Rotary Kiln	Augered-Bed Incinerator	Basket Grate
Dependability				
Prior art	1.5	2	3.5	3
Predictable wear	1.5	2	4	2.5
Total	3	4	7.5	5.5
Practicability				
Complexity	3	3	2	2
Ease of maintenance	2	2	3	3
Ease of operation	2.5	2.5	1.5	3.5
Total	7.5	7.5	6.5	8.5
Conservation				
Material recovery	2.5	2.5	2.5	2.5
Power consumption	2.5	3.5	2	2
Fuel consumption	4	2.5	1.5	2
Total	9	8.5	6	6.5
Environment				
Air	1.5	2	3.5	3
Water	2.5	2.5	2.5	2.5
Land	3	2	3	2
Total	7	6.5	9	7.5
Experience				
Number of installations	1.5	2.5	3	3
Operational history	1.5	2.5	3	3
Total	3	5	6	6
Economy				
First cost	2.5	3	2	2.5
Recurring costs	3	2	2	3
Total	5.5	5	4	5.5
Grand Total System Rating	35	36.5	39	39.5
Mean (Standard Deviation)	2.33 (0.75)	2.43 (0.46)	2.60 (0.76)	2.63 (0.48)
Percentile Score	56	52	47	46
Percentile Score Range	81-31	68-37	72-21	62-30

able length of time in mass-burning energy-recovery systems. Although the starved-air incinerator has had the longest operational experience of package systems (about 2.5 years), continuous operation (24 hr/day, 5 to 7 days/week) of this unit in an energy-recovery application has not been demonstrated. Both the recently developed augered-bed incinerator and the starved-air system show better promise for economic energy-recovery use than other package systems and warrant extensive and conclusive field testing vis-a-vis Army use.

Of field-erected waste-to-energy systems based on mass-burning, the generally technically superior system is the integrated waterwall incinerator using a multiple-tier, double reciprocating grate stoker.

Table 18

Comparative Ratings of Field-Erected Waste-to-Energy Combustion Systems

			Combustion in Modified Boilers					
	Mass-Burning (All Major Systems)	Coarse RDF I	Coarse RDF I	Coarse RDF II	Fluff RDF	Dust RDF	Densified Fluff RDF	Densified Dust RDF
Dependability								
Prior art	1	1.5	3	3.5	4	4	4	4
Predictable wear	2.5	1.5	2.5	3	3.5	4	4	4
Total	3.5	3	5.5	6.5	7.5	8	8	8
Practicability								
Complexity	2	1.5	2.5	3.5	3.5	4	4	4
Ease of maintenance	2	1.5	2.5	3.5	3.5	4	4	4
Ease of operation	2.5	2	2	4	4	3.5	3.5	3.5
Total	6.5	4	7	11	11	11.5	11.5	11.5
Conservation								
Material recovery	4	3.5	4	3.5	3.5	1.5	3.5	1.5
Power consumption	1	1.5	3	3.5	4	4	4	4
Fuel consumption	4	3.5	4	3.5	3	2	3.5	1.5
Total	9	8.5	11	10.5	10.5	7.5	11	7
Environment								
Air	3.5	3.5	3.5	3	3	2.5	3	3
Water	3.5	3.5	3.5	3	3	2.5	3	3
Land	4	3	3	3	3	3	3	3
Total	11	10	10	9	9	8	9	9
Experience								
Number of installations	1	1.5	3	3.5	4	4	4	4
Operational history	1	1.5	3	3.5	4	4	4	4
Total	2	3	6	7	8	8	8	8
Economy								
First cost	1	1.5	3	3.5	4	4	4	4
Recurring costs	1	1.5	3	3.5	4	4	4	4
Total	2	3	6	7	8	8	8	8
Grand Total System Rating	34	32.5	45.5	51	54	51	55.5	51.5
Mean (Standard Deviation)	2.27 (1.25)	2.17 (0.92)	3.03 (0.55)	3.40 (0.28)	3.60 (0.43)	3.40 (0.87)	3.70 (0.41)	3.43 (0.88)
Percentile Score	58	61	32	20	13	20	10	19
Percentile Score Range	99-16	92-30	51-14	29-11	28-0	49-0	24-0	48-0

Implementation of other stoking mechanisms and furnace configurations depends on the nature of waste generated at a particular site. The recently developed slag-forming incinerator has good theoretical potential for installation use, but requires test and evaluation before it can be recommended.

Use of both types of coarse RDF in package and field-erected systems of the type described above for mass-burning generally improves combustion performance and would theoretically improve system reliability. Use of coarse RDF in field-erected waterwall incinerators equipped with mechanical stokers can be recommended with acceptable confidence for handling larger installation waste streams. Application of package systems firing coarse RDF

Table 19

Comparative Ratings of Pyrolytic Conversion Systems

	Monsanto-Landgard Process	Garrett (Occidental) Process	Purox Process	Torrax Process
Dependability				
Prior art	2.5	2.5	2.5	2.5
Predictable wear	2	3	3	2
Total	4.5	5.5	5.5	4.5
Practicability				
Complexity	2	3	3	2
Ease of maintenance	2	3	3	2
Ease of operation	2.5	3	2.5	2
Total	6.5	9	8.5	6
Conservation				
Material recovery	3	2.5	2	2.5
Power consumption	2.5	2.5	3	2
Fuel consumption	2.5	2.5	2.5	2.5
Total	8	7.5	7.5	7
Environment				
Air	2.5	2.5	2.5	2.5
Water	2.5	2.5	2.5	2.5
Land	2.5	2.5	2.5	2.5
Total	7.5	7.5	7.5	7.5
Experience				
Number of installations	2.5	3	2	2.5
Operational history	2.5	3	2	2.5
Total	5	6	4	5
Economy				
First cost	2.5	2.5	3	2
Recurring costs	2.5	2.5	3	2
Total	5	5	6	4
Grand Total System Rating	36.5	40.5	39	34
Mean (Standard Deviation)	2.43 (0.26)	2.70 (0.25)	2.60 (0.39)	2.27 (0.26)
Percentile Score	52	43	47	58
Percentile Score Range	61-44	52-35	60-34	66-49

can be confidently recommended only after further demonstration. Use of other types of RDF in new combustion capital is currently under test and demonstration and is hence unproven as a reliable means of achieving improved waste disposal operations or conserving energy.

Use of RDF in existing Army-scale central boilers as a supplementary fuel is unproven, and such a venture would be experimental.

Systems for pyrolytic conversion of waste to a fuel gas or low-grade oil are currently under demonstration and are unproven for Army use. Because pyrolysis produces a more predictable and controllable fuel than solid RDF, it has high potential as a solution to the in-boiler RDF problem and warrants development for Army-scale use.

Anaerobic digestion systems are currently experimental. Methane recovery from landfills currently shows little potential for Army use due to the relatively small size of typical Army landfills. Controlled digestion shows little potential due to its operational complexity and high cost.

10 DIRECTION OF FUTURE RESEARCH

The technological and economic aspects of the waste-to-energy area are dynamic. Evaluation of technical improvements in systems having high potential for Army use should be continued, and thorough field testing of smaller waste-to-energy systems which have potential for economic Army-scale use should be conducted. The potential impact of materials recovery guidelines (such as paper recycling) on the general economic feasibility of using installation waste as an energy resource should be evaluated. As technological improvements continue to be made in systems showing potential for Army use, continued efforts at updating guide specifications for fuel handling, combustion, and energy-recovery apparatus are warranted. Development of a reliable method of surveying installation solid waste and determining energy-recovery system design parameters is also needed.

REFERENCES

Combustion Performance Tests of Ecofuel II at Weyerhauser Company, Fitchburg, Mass. (York Research Corporation, 1974).

Design Manual-Mechanical Engineering (Naval Facilities Engineering Command, 1972), p 3-2-5.

Facilities Engineering: Annual Summary of Operations for FY 75 (Office of the Chief of Engineers, 1976).

Final Report for Erie County-Torrax Solid Waste Demonstration Project (Carborundum Environmental Systems, Inc., Torrax Division, May 1974).

Fryling, G., ed., *Combustion Engineering* (Combustion Engineering, Inc., 1966).

Fuels from Municipal Refuse for Utilities: Technology Assessment (Bechtel Corporation, March 1975).

Hathaway, S. A., A. N. Collishaw, and J. P. Woodyard, *Technical Evaluation Study: Energy Recovery Incineration of Solid Waste at Naval Weapons Support Center, Crane, IN*, Technical Report (U.S. Army Construction Engineering Research Laboratory [CERL], 1977).

Hathaway, S. A. and J. P. Woodyard, *Technical Evaluation Study: Solid Waste as an Energy Resource at Quantico Marine Base, VA*, Technical Report E-93 (CERL, 1976).

Hathaway, S. A. and J. P. Woodyard, *Technical Evaluation Study: Solid Waste as a Fuel at Fort Bragg, NC*, Technical Report E-95/ADA034416 (CERL, 1976).

Hathaway, S. A., J. S. Lin, A. N. Collishaw, *Design Concept for Densified RDF Production and Handling Systems in Military-Scale Applications*, Draft Technical Report (CERL, 1977).

Linaweaver, F. P. "Baltimore to Use Pyrolysis for Refuse Disposal," *Public Works Magazine* (March 1974).

McFarland, A., et al., *Control Technology for Toxic and Hazardous Air Pollutants*, Document 75-6 (Illinois Institute for Environmental Quality, April 1975).

Moore, J., "More Cities Find New Disposal Systems Fail to Meet Cost and Performance Goals," *Wall Street Journal* (21 July 1976), p 28.

Pfeffer, John T., *Reclamation of Energy From Organic Refuse: Anaerobic Digestion Process*, presented at the Third National Congress on Waste Management Technology and Resource Recovery, San Francisco, CA (14-15 November 1974).

Refuse Incinerator/Heat Reclamation Facility, Naval Station Mayport, FL (Greenleaf/Telesca, Planners, Engineers, Architects, Inc., 1975), pp V-13 – V-17.

Rigo, H. G., "Characteristics of Military Refuse," *Proceedings of the ARPA Workshop on Waste-to Energy Conversion Systems for Military Base Utilization*, P. Beltz and J. Frankosky, eds. (Battelle Columbus Laboratories, 1974), p C-23.

Rigo, H. G. and M. E. Eifert, *Technical and Economic Review of NCRR Grant Application Entitled Preparation, Use and Cost of d-RDF as a Supplementary Fuel in Stoker Fired Boilers* (Systems Technology Corporation, June 1975), pp A1, A2, B1, B2.

Rigo, H. G., S. A. Hathaway, and F. C. Hildebrand, *Preparation and Use of Refuse-Derived Fuels in Industrial Scale Applications*, presented at the First International Confernce on Conversion of Refuse to Energy, Montreux, Switzerland, 3 November 1975.

Rigo, H. G., D. N. Nelson, and M. E. Elbe, *Technical Evaluation Study: Solid Waste Generation and Disposal at Red River Army Depot, Texarkana, TX*, Technical Report E-33/AD779509 (CERL, 1974).

Rueth, N., "Can America Survive Materials Shortages?", *Mechanical Engineering*, Vol 97, No. 1 (January 1975), pp. 29-33.

Savage, G. and G. Trezek, "On Grinder Wear in Refuse Comminution," *Concept Science* (September-October 1974).

Schanche, G. W., L. Greep, and B. Donahue, *Installation Solid Waste Survey Guidelines*, Technical Report E-75/ADA018879 (CERL, 1975).

Schutz, H., "Energy from Municipal Refuse: A Comparison of Ten Processes," *Professional Engineer* (March 1976).

Schwieger, R., "Power from Waste," *Power* (February 1975).

Smith, M. and K. Stinson, *Fuel and Combustion* (McGraw-Hill, 1952).

Snyder, N. W., "Energy Recovery and Resource Recycling," *Chemical Engineering* (October 21, 1974), pp 65-72.

Solid Waste Fuel Modification, Second Series, Burn Tests—Final Report (Eugene Water and Electric Board, 1974).

Weinstein, N. and R. Toro, *Thermal Processing of Municipal Solid Waste for Resource and Energy Recovery* (Ann Arbor Science, 1976).

Woodyard, J. P., *The Prediction of Solid Waste Generation: A Review*, Master's Thesis (Department of Mechanical Engineering, University of Illinois, 1976), p 68.

APPENDIX A:

USE OF SUPPLEMENTARY REFUSE-DERIVED FUEL IN ARMY CENTRAL STEAM GENERATORS

Introduction

The advantages of using installation mixed solid waste (MSW) as an energy resource are self-evident. Combustible materials which otherwise would be wasted are used as a resource, thus conserving their equivalent energy value in increasingly costly and scarce conventional fuels. Waste volume reduction ranging up to 98 percent may be achieved, bringing similar increases in the functional lives of ultimate waste disposal modes such as landfills. The essentially inert residue produced can be landfilled in a manner more environmentally acceptable than can putrescible trash and garbage.

Demonstration of refuse-derived fuel (RDF) as a supplementary fuel in existing boilers began at the Union Electric Meramec Plant in St. Louis in 1972. RDF is tangentially cofired in suspension with pulverized coal at a substitution rate ranging to 20 percent in two modified 925,000 lb/hr (419 571 kg/hr) utility boilers. Interest aroused by this apparent success led to planned construction of numerous similar RDF facilities in major municipalities throughout the United States. The possibility of using RDF as a supplementary fuel in Army central steam generators has also aroused interest. This appendix reviews some of the technical factors affecting potential adaptation of existing Army boilers to RDF use. Emphasis is placed on the combustion of RDF coal mixtures by mechanical stoking in field-erected boilers designed to produce saturated, medium pressure steam in the capacity range of 30,000 to 100,000 lb/h. (8523 to 28 410 kW).

Generic Types of RDF

The generic types of RDF are described in Chapter 5 of the main text.

Solid Fuels and Design

Even the simplest boiler fuel is complex. A specific coal or RDF can be composed of an almost endless number of chemical combinations of hydrogen, carbon, and mineral matter. Adequate design must carefully account for boiler mission, fuel source, physical and chemical characteristics of the fuel, and the potential variability of those critical characteristics.

Boiler "mission" refers to the functional purpose of the boiler. Most Army central boilers produce medium-pressure saturated steam for heating, cooling, and, in some cases, processes. An important consideration in the design of Army central boilers has been future requirements, such as extended steam distribution, added loads, or the possibility of fuel changeover. Frequently, "designs" for conversion from oil to coal have been little more than hatched areas on original blueprints, making actual conversion an extensive and costly task.

Fuel source plays such an important role in boiler design that long-term fuel supply agreements are often made before design has commenced. The common layman practice of classifying boiler fuels by broad geographic region (i.e., Midwest vs. Eastern bituminous coal) is inadequate for design. Coal sources, for example, are usually specified in terms of state, city or county, seam, company, and mine. Some fuels may be required to meet mythical-source specifications. Knowledge of fuel source or specification allows the designer to establish fuel design parameters with the aid of laboratory analyses.

A fuel ultimate analysis reveals the fuel's exact elemental composition. With the higher (ash- and moisture-free) and lower (as-fired) heating values (HHV and LHV), the analysis provides the data required to complete combustion calculations and to predict boiler efficiency.

The fuel proximate analysis provides data by which to predict performance of the fuel in the boiler. This analysis discloses the fuel content of volatile matter, moisture, ash, and fixed carbon. Volatile matter includes combustible gases and vapors given off by high-temperature distillation and decomposition of the fuel. Sometimes referred to as "inerts," ash is essentially incombustible solid matter in the fuel. Fixed carbon is carbonaceous residue in the fuel after volatiles have been driven off; it generally represents that fraction of the fuel which must be burned in the solid phase. The form and hardness of fixed carbon are an indication of the fuel coking properties.

To obtain a clear picture of the ignition rate, a fuel burning profile is established. The profile shows the rate of reaction, or time required for volatilization, and is usually expresed as the rate of fuel weight loss as a function of furnace temperature.

Ash characteristics are critical. The ash sintering strength (comparative compressive strength of sintered ash) is established to indicate its potential erosiveness. The viscosity-temperature relationship must also be known, since "plastic" ash causes problems in furnaces. Ash fusion temperatures are reported in terms of initial deformation, softening, and fluid temperatures. Spectrographic analysis reveals the basic elemental composition of the ash and indicates fouling tendency. While the presence of sulfur and some halogens (principally chlorides) do not usually directly affect combustion, they are important from the standpoint of corrosion.

Of vital importance in boiler design is knowledge of the variability of fuel characteristics. Fuel variability occurs at any scale, from region to geographic region, and from inch to inch in the same seam or pool. Knowing the range of variability, the designer can establish the slagging and fouling characteristics of the most adverse, or "design," fuel, and can thereby specify the furnace and heat transfer surfaces to occasionally tolerate the worst case fuel with an acceptable degree of safety.

Boiler RDF Conversion

The customary approach to evaluating the capability of an existing Army-scale central boiler to fire supplementary RDF involves comprehensive rigorous redesign of the unit for what is, in effect, a new, downgraded fuel. Required design is compared to existing design, and a determination is made as to the extent to which capital modifications are required. Subsequent economic analyses disclose whether the venture is profitable and should be further pursued.

Experience with boiler modification, fuel substitution, and RDF use in smaller scale systems has been conservative to date. While supplementary cofiring of RDF at substitution ratios up to 25 percent by LHV with no combustor modification may be demonstrably practicable on a very temporary basis, boiler mission may be substantially jeopardized by continuing such practice, because the margin of designed combustor tolerance for a "worst case" fuel is consideraoly narrowed.

RDF as a Fuel

Typical RDF characteristics differ dramatically from those of conventional solid boiler fuels (Table 6 in text). RDF moisture content compares to that of lignite. Ash content can be three times greater than that of any coal, while most coals have at least twice the amount of fixed carbon. Some types of RDF can contain a comparatively high percentage of volatile matter, but it is not necessarily as reactive as that of most coals. Oxygen and nitrogen contents of RDF are about twice as high as those of most coals, while the hydrogen content is usually about the same, and the carbon content is less. RDF has from one-third to one-half the heating value of typical coals. Although RDF has a lower sulfur content, this advantage is more than offset by usually higher fractions of halogen, lead, and zinc compounds. On the whole, RDF is potentially more corrosive. Ash fusion temperatures are lower, due to the presence of relatively large amounts of glass and ferro-aluminum materials, and hence the propensity for slagging and fouling is greater.

Typical RDF fuel characteristics mean little in practice. The generation rate and physical-chemical nature of MSW are highly variable over short increments of time both at a single location and among numerous locations (Figures 2 and 3 in text). Due to the dynamic time- and space-distributed nature of MSW parameters, specification of a design RDF in terms of quantity and quality can be extremely difficult (Table 5 in text). If RDF is to be used to meet an MSW disposal requirement, system design development often must be done by combining procedures which have been developed and used separately for incinerators and boilers and which are almost mutually exclusive. Incinerator systems are usually sized to accommodate peak MSW loads, since they must respond to a continuing waste disposal requirement. Steam generators, however, are designed for optimal performance using a fixed amount of design fuel.

RDF performance predictability can be improved by reducing its variability. Efforts at achieving this have included recommending multi-day storage facilities for either MSW or RDF, mixing, and adding unit operations to generic RDF processing lines. These steps are aimed at making the characteristics of each load of RDF fed to a combustor closer to the statistically average characteristics of all loads. This goal may also be achieved by using RDF only at extremely low substitution ratios where load variability approaches that of the design fuel. Except for very large systems where a great absolute quantity of MSW is to be processed, this approach will generally drive a system concept well below the threshold point at which it is cost-effective. Economy also plays a leading role when lengthy and complex RDF processing lines are considered. Additional skilled operating labor is usually required, maintenance costs increase, and the reliability of the total system declines. Taking this approach means adding value to an essentially "free" energy resource, often beyond the point at which conventional boiler fuels are competitive.

Fuel Burning Equipment

It presently appears that if RDF is to be seriously considered for use as a supplementary fuel in comparatively small Army central boilers, it will in most cases be cofired with coal on a mechanical stoker. Many Army central boilers now firing fuel oil and/or natural gas were originally designed for coal; about a decade ago they were converted to cleaner fuels for environmental reasons. Numerous others were designed for oil and now face the more difficult problem of conversion to a dirtier, solid phase fuel. Of chief concern in this report is the most common case—cofiring RDF and design coal in an Army central scale boiler equipped with a mechanical stoker.

Combustors are classified by type as suspension-burning, cyclone-burning, or fuel bed-burning. Coal-fired boilers generally fall into broad classes which depend greatly on the size and characteristics of the coal to be fired. Some combustors are more tolerant of qualitative fuel differences than others; some are designed specifically to handle a wide variety of coal characteristics, while others are designed to take advantage of selected characteristics such as size, guidability, moisture, volatile matter, ash-fusion temperature, and free-swelling index. Spreader stoker units generally can handle a wide variety of coals, except anthracite, but show moderate sensitivity to fuel size consist. The hopper-fed traveling chain grate is felt to have the capability to handle every type of solid fuel but strongly caking bituminous coals. Limiting factors are moisture content and low to medium (4-6) free-swelling index. Fuel selection for this stoker requires special attention to the combination of size consist versus the degree of free burning. Slagtap furnaces require a coal with an ash-fusion temperature generally between 2000 and 2600°F (1093 and 1427°C); ash is removed in molten form from the walls of the furnace. Single-retort stokers burn a wide variety of coals with varying success; size consist, ash fusibility, and caking tendency influence performance. In contrast, multiple-retort stokers perform best when fired with caking Eastern bituminous coals. The *general* relationships between fuel characteristics and combustor performance are shown in Table A1. The combination of two or more properties changes the relative significance of a single item, and effects are not necessarily additive.

In the types of Army boilers which are potential candidates for RDF use, the furnace is the "burner," serving as both a mixing chamber and heat exchanger. If boiler rating is to be maintained while a lower grade fuel (coal and supplementary RDF) is fired, a greater quantity of fuel must be fed to the furnace per unit time. With even small decreases in fuel LHV, the required feed rate rapidly increases. Maintaining constant, optimum fuel bed depth at higher feed rates requires increasing stoker speed. With increased RDF to coal ratios, the required stoker speed rate can attain and even exceed the design maximum. This condition brings about decreases in fuel residence time, resulting in incomplete combustion of the coal-RDF mixture, passage of flaming particles to the ash hopper, and general decline of fuel-to-steam conversion efficiency. Available grate area is hence a major factor limiting supplementary RDF use.

The physical nature of RDF particles is likewise of concern. Finely shredded RDF will inevitably foul most grates used for coal firing. Densified RDF is seen as a step toward solving this problem. However, currently manufactured fluff-derived pellets readily lose their structural integrity on the grate, resulting in fouling. Experience has shown that RDF pellets produced by mechanical extrusion readily break apart at the interfaces between plastic or metal fragments and the light, more cohesive, cellulosic fraction (Figure A1). Certain of these metallic compounds may melt in the hotter zones of the fuel bed and solidify on the cooler grate. With the unpredictably variable presence of highly volatile materials in RDF, such as film or foam plastics and some metallic compounds, the furnace front-wall and grate are susceptible to excessive thermal stress as flashes occur. Grate-firing of dust-derived pellets has a similar low potential; heavier fines liberated as the pellets disintegrate under high temperatures readily sift through the grate, while underfire air forces lighter particulate material upward into the gas stream.

Table A1

Combustion Performance Table for Solid Fuel Properties

Very Important 1 Important 2 Minor Importance 3 Little Importance 4 Solid Fuel Property	Solid Fuel Firing Method			
	Underfed Single Retort	Underfed Multiple Retort	Traveling Grate	Spreader Stoker
As-Fired Size Consist	1	2	2	1
Moisture	3	3	4	3
Caking Index	2	2	1	3
Ash Fusibility	2	2	3	3
Grindability	4	4	4	4
Friability	3	3	3	3
Volatile Matter	3	3	3	3
Fixed Carbon	4	4	4	4
Ash Content	3	3	2	3
Heating Value	4	4	4	4
Ash Viscosity	3	3	3	3
Ash Composition	*			
Sulfur	**			
Chlorides	**			

*Affects fireside fouling; not important to combustion.

**Important from corrosion standpoint, not vital to combustion.

When cofiring RDF, combustion air requirements can exceed those for coal alone by as much as 50 percent. Increased underfire air velocity disrupts fuel bed integrity, entraining lighter RDF particles in the flue gas. Carryover of burning particles of the supplementary fuel to screen tube and downstream convective areas is usually unavoidable.

Flame travel distance is another critical parameter. Flame heights up to 30 percent greater than experienced with coal alone are not unusual at even small RDF substitution ratios. By increasing underfire and overfire air to meet combustion requirements, flame is forced further up into the available furnace volume. Flame impingement on backwall and roof, and possibly on screen tube sections, may be anticipated, along with accelerated material wastage in such areas.

Increased combustion air requirement is a major limiting factor in RDF use. A greater absolute quantity of energy is lost, both to heating cold air entering the furnace and to evaporating the moisture it contains. Heat losses to moisture are major, because large masses of air are required for combustion, and RDF moisture content can be more than three times that of the design coal. Heat loss penalties paid in using supplementary RDF reduce the relative economy, and hence the major justification of using the waste fuel. With increased combustion air, gas flow rates and velocities through the steam generator can exceed design specification. New flow fields can develop in the furnace which can be neither analytically defined nor predicted. Similarly, the synergistic effects of increased gas velocity, newly established flow fields, and increased gas particulate loading on both furnace surface longevity and boiler efficiency cannot be rigorously predicted.

Transfer of Heat

The mission common to all Army central steam plants is to economically produce the heat and energy required at the installation. Nearly all Army central boilers are of the waterwall watertube type, in which heated combustion products pass over tubes carrying only treated water and the product steam. The main functions of the system are hence to completely burn the fuel and to cool the combustion products sufficiently so that downstream convective passes can be maintained in a satisfactorily clean condition with a reasonable amount of maintenance. The methods of heat transfer employed to cool the gases, vapors, and solids liberated in the fuel combustion process are radiation, convection, and conduction, with the latter usually being least important.

The amount of radiative heat transfer in a furnace depends directly on the extent of hot surfaces and the difference of the fourth powers of the abso-

a. Before.

b. After.

Figure A1. Structural deterioration of fluff-parent RDF pellets after passing through typical coal-conveying system at boiler plant.

lute temperatures of the cooler absorbing surfaces and the hot surfaces. The basic relationship is:

$$q = \epsilon A \sigma (T_1^4 - T_2^4) \qquad \text{[Eq A1]}$$

where

q = the radiative heat transfer rate
ϵ = the emissivity of the radiating element
σ = the Boltzmann constant
T_1 and T_2 = the absolute temperatures of the heat source and sink, respectively (an expression of the "thermal gradient").

Tubes near the flame which do not have a high rate of gas flowing across them receive nearly all their heat by radiation. In cofiring RDF, flame temperatures can be as much as 20 percent lower than when firing the design coal alone, and emissivity is normally somewhat lower. Increased flame size does not compensate for these decreases. Because of the "fourth power" temperature law, moderate decreases in flame and furnace temperature dramatically reduce the rate and amount of heat absorbed by furnace surfaces. At typical operating temperatures, the amount of heat transferred in a unit time is reduced by half for every 19 percent decrease in the absolute temperature of the radiating source.

The rate of convective heat transfer from hot combustion products to water-cooled tubes depends on the temperature and velocity of the gases and the rate at which cooler heat-absorbing media flow through the tubes. In typical small-scale boiler designs, the rate of convective heat transfer is much less important than that of radiative transfer. In assessing boiler performance, the convective rate often appears as a relatively small correction factor applied to the more dominant radiative rate. Allowable flue gas velocities limit the rate of convective heat transfer. Increased gas flow rates, which arise when cofiring RDF, generally mean increased convective heat transfer rates in the narrower downstream passes of the boiler. However, pressure drop through the boiler increases with the square of velocity, and blower power requirement rises with its third power. Hence, while doubling gas velocity increases the rate of convective heat transfer, it also increases the pressure drop four times and the fan power requirement eight times. With greater gas velocities, the potential of surface erosion by fly ash particles is considerably enhanced. The velocity of heat-absorbing media through tubes is limited unless circulating pumps are installed.

Some Army central boilers which are candidates for RDF cofiring have screen tubes after the furnace to cool exit gases before they enter the more restricted convective area. Screen tube performance is directly affected by gas flow rate and temperature. Gas temperature drop per tube row will be somewhat less than optimal when cofiring RDF. Gas velocity through the free gas area in the screen bank can be sufficiently great to result in accelerated surface erosion. Baffles can be installed to ameliorate such problems in erosion prone zones. Tubes in the screen bank can sometimes be removed to enlarge the free gas area, with bank lengthening done to compensate for the initial extraction of heat-absorbing surface area.

Although gas velocities to the convective section are higher than optimal when cofiring RDF, temperatures can be lower than what an existing design demands, resulting in a substantially reduced log mean temperature difference across the convective bank. With increased moisture in the combustion products when cofiring substantial amounts of RDF, the rate of nonluminous radiative heat transfer can be higher than optimal. However, the rates of convective and *total* heat transfer are lower. The existing boiler heat-absorbing surface area is apt to be inadequate to maintain acceptable thermal balances. Numerous limiting factors indicate the necessity of resetting tubes in the boiler convective section if acceptable efficiencies are to be maintained when cofiring RDF at economic levels of substitution. Minimum practical spacing of tubes is determined by draft loss, gas velocity, and erosion potential. In cofiring RDF, each of these parameters can increase substantially.

Combustor Auxiliaries

Installation of sootblowers is imperative if the furnace and boiler are to be satisfactorily operated when cofiring RDF on a regular basis. With greater ash content and lower ash fusion temperatures, soot-blowing requirements are greater when cofiring RDF than when firing coal alone. Use of RDF will normally require more soot-blowing capability than provided by an original coal design, and probable relocation of ports.

Due to increased mass flow rates, furnace draft loss is greater. With higher moisture content in the combustion products, less tempering air is admitted downstream, and more air must be directly forced into the furnace by the forced draft (FD) fan. If a typical Army-scale boiler is to be converted to a downgraded fuel, FD fans installed for the higher grade design fuel normally must be replaced with units of larger capacity and power consumption. Induced draft (ID) fan requirements are determined largely by ash load and composition. The type of air pollution control equipment used and the tendency of convective areas to foul and plug set the limits on ID fan size and static requirements. If RDF is to be cofired, ID fans will require replacement with larger units. O&M costs will rise, because the ID fan will be subject to greater wear due to increased loading and abrasiveness of ash.

Higher mass flow rates through the furnace and boiler normally will require reevaluation of stack parameters. Stack height usually must be increased; however, replacing a stack with one of comparable height but greater cross-sectional area may be possible in some cases.

Use of a higher ash fuel, which requires greater quantities of combustion air, normally causes an adverse shift in the particulate collection efficiency of existing air pollution control equipment. Existing apparatus is hence rendered inadequate in reducing emissions to acceptable levels. Either new or supplementary air pollution control hardware must be installed; its design must be responsive to higher particulate load, increased gas flow rates, a new particulate size distribution, elevated potential for cold-end acid attack, and the unique physical-chemical properties of the ash.

Surface Effects

A furnace is a large, heterogeneous turbulent chemical reactor in which fuel is intimately mixed with air to produce high-temperature combustion products. For a system to function satisfactorily, heat transfer surfaces must be kept clean and intact. Slagging, fouling, and corrosion create deleterious effects which are revealed in poor system performance and fuel economy (Figure A2).

When a coal RDF mixture enters a furnace, mineral matter in the fuel is suddenly liberated from its organic matrix. This matter can remain a solid and either pass through the system as fly ash or deposit on interior surfaces, or the liberated mineral matter can melt to a liquid which may

Figure A2. Example of furnace frontwall slagging in military-scale coal-fired boiler equipped with traveling chain grate.

either adhere to furnace surfaces or volatilize and condense on surfaces downsteam from the furnace. All of these processes may occur simultaneously, along with chemical reactions between ash constituents, deposits, surface materials, and fly ash particles. At a given instant, the physical-chemical character of ash is changing in response to the formation and interaction of complex compounds in a furnace environment where temperatures constantly fluctuate and reaction atmospheres vary from oxidizing to reducing.

Fouling refers to the accumulation of ash and residue in gas passages or on heat-absorbing surfaces; it usually results from undesirable restrictions to the flow of gas or heat. These flow restrictions may result from residue build-up, or from free gas areas that are too small to accommodate the larger mass flow rates through the system when a lower grade of fuel such as a coal-RDF mixture is burned. Fouling often involves high-temperature bonded deposits caused by volatilization of elements from the ash and selective condensation on cool surfaces. Deposits also result from direct impact of ash. The rate of deposition is strongly influenced by the quantity of ash passing over the surface per unit time. The higher ash content of RDF creates a greater tendency for surface fouling than when the design fuel alone is fired.

The fouling rate also depends on the size distribution of the residue. Volatile components of the flue gas generally behave aerodynamically like gas molecules and deposit by molecular diffusion. When gas velocities are high, this mechanism becomes negligible. For larger particles, whose path of travel is less affected by changing gas direction and velocity, deposition occurs mainly by inertial impaction. There are, however, few hard rules involving the deposition mechanism. Because of the heterogeneous nature of the particle suspension and the fact that gas velocity, temperature, ash concentration, and size distribution are always changing, it is likely that numerous deposition processes occur simultaneously.

Slag is essentially molten or fused ash. Slagging, which refers to fused slag deposits which form on surfaces, normally occurs on surfaces exposed to radiant heat (the hottest part of the furnace) and is associated with the transport of molten or sticky particles and the formation of local, dense, hard deposits. Slag with a viscosity up to 250 poise (25 N.s/m^2) is usually not a problem in furnaces, since it normally is sufficiently fluid to "wash" from the surfaces to which it is transported. However, temperatures high enough to sustain low-viscosity slag are not usually found in small-scale furnaces. "Plastic" slag in the viscosity range between 250 and 10,000 poise (25 and 1000 N.s/m^2) is most problematic. Ash fusion temperatures of RDF are substantially lower than those of coal, due largely to the presence of glass and ferro-aluminum compounds (Table A2). Potentially severe slagging problems with RDF at temperatures typically encountered in Army-scale systems can be anticipated.

The principal deleterious effects of slag are a reduction of heat transfer due to buildup on absorbing surfaces and to surface wastage. Numerous surface wastage mechanisms have been proposed, all of which are probably occurring simultaneously. It is known that furnace wall tubes develop an outer layer of protective iron oxide coating when exposed to high temperatures. According to one theory, the oxide layer is covered with alkali (sodium, potassium) sulfates from the furnace atmosphere. An ash layer accumulates on the alkali layer. As the ash layer becomes thicker, the thermal gradient through it decreases, and the exposed outer layer melts. Increased temperature within the deposit leads to dissociations of sulfates to release sulfur trioxide which migrates to the cooler oxide-covered metal surface. The sulfur trioxide reacts with the alkali sulfates and iron oxide, dissolving the protective iron oxide layer and forming alkali iron trisulfates. After deslagging occurs, normally with load change, the layer spalls off and the tube metal again oxidizes to reestablish its normal protective oxide film. This reoxidation causes irreversible loss of metal.

According to the second proposed wastage mechanism, unbonded fly ash accumulates on the oxide layer of the tube, and alkalis from within this ash deposit form sulfates with sulfur trioxide from the gas stream. Alkali sulfates in turn react with additional sulfur trioxide and the iron oxide in the ash deposit to produce alkali iron trisulfates, which migrate as molten compounds through the ash deposit as a result of the normal thermal gradient in the deposit. The molten alkali iron trisulfates accumulating at the interface between the tube metal and the deposit react with the tube metal to cause wastage, since the liquid phase is rich in sulfate ion.

In each of these surface wastage mechanisms, sulfur and sodium, which are ubiquitous in typical

Table A2

Fusion Temperatures of Residue Constituents and Melting Points of Pure Metals

	Initial Deformation	Softening (oxidizing atmosphere)	Fluid
Clear Glass	1480 (804)	1680 (916)	1840 (1004)
Brown Glass	1620 (882)	1740 (949)	2080 (1138)
Green Glass	1640 (893)	1800 (982)	2080 (1138)
Ash from			
Garbage	2020 (1104)	2140 (1171)	2200 (1204)
Cardboard, corrugated	2060 (1126)	2160 (1182)	2240 (1227)
Misc. paper	2160 (1182)	2300 (1260)	2480 (1360)
Grass and dirt	2080 (1138)	2240 (1227)	2320 (1271)
Textiles	2040 (1116)	2180 (1193)	2240 (1227)
Heavy plastics, leather, rubber	2100 (1149)	2220 (1216)	2300 (1260)
Bones and shells	2800 (1538)	2800 (1538)	2800 (1538)
			Melting Points, °F (°C)
Iron			2795 (1535)
Iron oxide (Fe_2O_3)			2849 (1565)
Aluminum			1200 (649)
Aluminum oxide (Al_2O_3)			3713 (2045)
Lead			622 (328)
Tin			449 (232)
Zinc			769 (409)
Lime (CaO)			4676 (2580)
Silicon oxide (SiO_2)			2930 (1610)

installation MSW and potential RDF, play important roles. Use of sodium-sulfur compounds as embrittling additives in the manufacture of dust RDF is seriously questionable from the standpoint of potential deleterious surface effects within the combustor.

Other research on furnace tube wastage has shown that continuous or intermittent impingement of flame plays an important role, and that affected tubes are "washed" by flowing slag within areas where there is impingement. It has also been shown that local variations in furnace atmosphere from oxidizing to reducing play an important role in surface wastage. Such changes cause removal of the protective iron oxide layer on tubes.

Three major corrosion mechanisms can be expected to occur in any furnace fired with coal and coal-RDF mixtures. First, carbon monoxide and hydrogen sulfide are produced as products of partial combustion in a reducing atmosphere and cause tube failure by directly reducing the protective iron oxide layer on the tubes. The second mechanism, attributed to halogens present in relatively great quantities in RDF and to a lesser extent in coal, is exemplified by direct attack on metal by very aggressive hot chloride compounds. Finally, low-temperature corrosion occurs at cold ends of systems when the flue gas contacts surfaces whose temperatures are below the dewpoint of corrosive constituents of the gas. In addition, some deposits are corrosive; where these deposits are hygroscopic, the severity of the problem increases with length of outage. There is general agreement that corrosion problems experienced when burning refuse or RDF result from the presence of chlorine, sulfur, lead, zinc, sodium, and potassium in the flue gases and in ash deposited on surfaces, and that the persistence of a fluctuating oxidizing/reducing atmosphere is a significant factor in metal wastage.

Handling RDF

Although economy of using RDF in small-scale applications is partially determined by the capability of existing solid-fuel-handling and storage equipment to accommodate the fuel, design requirements for storage and flow have been among the most overlooked factors in the evaluation of RDF systems. It has frequently been taken for granted that if an Army central steam plant has

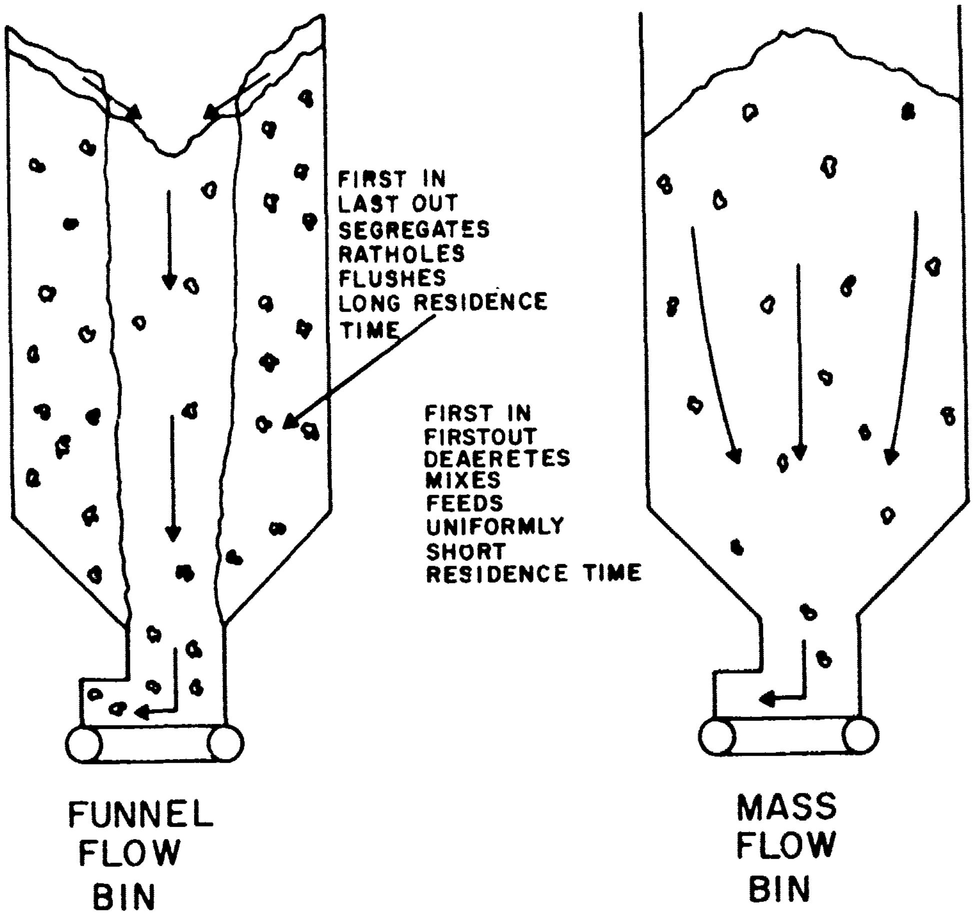


Figure A3. Funnel and mass flow bins. Mass flow bin is recommended for RDF.

solid-fuel-handling and storage facilities (which most often were designed for a particular coal), then these facilities can adequately be used for various forms of RDF. Field experience in small-scale RDF systems indicates that quite the opposite is true.

A bulk solid's flowability is affected by particle size and nature, bulk density, moisture content, temperature, and time of storage at rest. These factors determine whether any form of RDF can successfully be used in coal-handling systems.

The adaptability of coal-handling systems to RDF cannot be quickly determined by using analogies to fluid flow, as might be thought. Unlike fluids, solids have a static angle of internal friction greater than zero (i.e., static pressures in a solid are not independent of direction, and hence a solid can transfer shearing stresses under static conditions). The shear stresses in a solid depend on the mean pressure within the solid and not on the rate of shear. Consolidated solids have cohesive strength and retain their shape under load. As a flowing solid is compacted in a channel (such as a coal hopper), this cohesive strength increases, often until it is great enough to support the weight of the solid; flow then ceases.

The essential flow requirement of RDF is mass flow—a first-in, first-out storage method—as opposed to funnel flow, where a stagnant volume of solid forms around the bin's outlet (Figure A3). Since a mass flow system has no stagnant volume, the potential for biological, chemical, and physical degradation of RDF is minimized. A bin designed for mass flow provides for uniform discharge rate at uniform material density, keeps material segregation at a minimum, has increased effective storage capacity (due to no stagnant volume), and permits reliable operation of the system into which it is integrated.

Whether a solid will flow freely from a hopper depends essentially on its flowability and the flow function of the hopper. The flow function for a particular hopper is related to its geometry, the size of the outlet, and the presence of wall obstructions. Highly flowable solids such as dry sand will flow easily from any hopper designed for coal, since dry sand cannot be consolidated at pressures normally encountered in coal bins. If moisture is added to the sand, it gains strength and may more readily become consolidated under low pressure, thus restricting its flowability. A flow aid such as a bin vibrator may be successfully used to, in effect, change the hopper flow factor to accommodate flow.

In a test of RDF in a small-scale boiler, a substantial mass of densified RDF was placed into a hopper designed for a Midwestern bituminous coal. Withdrawal of the RDF was extremely difficult (Figure A4, Subsequent analyses showed that a number of important variables were at play in the no-flow condition. The RDF particle size was subsantially different from that of coal (shredded paper with ¼ in. [6 mm] top size vs. 1½ in. [38 mm] coal). The RDF bulk density was only 40 percent that of coal, while RDF moisture content was nearly three times that of the design coal. The RDF was highly fibrous. As the RDF resided in the hopper, the pellet structure rapidly deteriorated under modest pressures, forming a solid mat strengthened by lacing and intertwining of the fibers (Figure A5). Migrating moisture strengthened the bottom of the mass, further reducing flowability in critical areas near outlets. Moisture and heat in the RDF accelerated chemical and biological activity, which resulted in harborage of insects and finally, under increasing pressure, actual combustion in the bottom of the mass. Rapping the bin and hopper and using a vibrator did not improve flow; instead, it caused the RDF to further consolidate. The problem was solved by saturating the RDF with water; fluidization increased flowability, and the mass was washed from the hopper.

Further analyses and field inspections have clearly shown that hoppers designed for coal at Army installations will not tolerate currently produced RDF. The analyses have also indicated that some hoppers are questionably designed for the coal they currently handle, indicating that severe flow problems are likely even when a coal-RDF mixture is placed in them. At present, no form of RDF is being economically produced which can be reliably handled in coal hoppers of the type commonly found at Army installations.

Conventional coal-conveying systems are likewise of questionable utility in handling densified RDF. Under vibrations usually encountered in coal-conveying systems, the pellet structure of RDF will deteriorate, detracting from fuel quality. Substantial quantities of fine, fibrous fugitive dust are released into the plant atmosphere as RDF passes through the existing coal-handling equipment and is dumped into the storage bunker. When draft is low, dust suspensions in bunker areas can be potentially explosive. Pneumatic transport of the material is similarly not without problems. Abrasive materials in the fuel abrade line material at turns, necessitating placement of retardant materials, usually steel alloy or ceramic plates. Resistant materials in the RDF can damage fans and housing, misshaping them and causing sparks which can bring about fire and explosion in the lines.

Methods of mixing RDF and coal in small-scale systems have received very little technical attention. Ideally, a perfect RDF-coal mixture with equal RDF to coal ratios at all points in the fuel bed should be achieved. Mixing can take place at the point of fuel delivery to the plant, in the coal storage hopper, between the hopper and the furnace, or in the furnace.

In-furnace blending of fuels for grate firing is most difficult to achieve. Unlike suspension-cofiring where the RDF enters the furnace through a separate burner, grate firing systems have no inherent means of achieving high quality in-furnace mixing of two or more separate solid fuels. If mixing of coal and RDF is achieved before or in existing storage hoppers, risk of a severe no-flow condition of the fuel mixture is great. Mixing at these points can be recommended only if existing storage facilities are modified or if new facilities are added which are designed to accommodate fuel flow properties. Mixing between the storage hoppers and furnace is normally achieved at the feed to the furnace. In the case of spreader-stoker-fired units, the RDF enters the coal stream just above the impeller. For gravity-fed travelling chain grate furnaces, the RDF is blended with the coal at the feed hopper.

Achieving adequate mixing requires agitation of coal and RDF together. Currently produced RDF pellets cannot, however, retain their shape when mixed with even minor vigor with harder coal. The RDF pellet disintegrates, thus enhancing the potential of grate fouling. It is felt that slowly converging

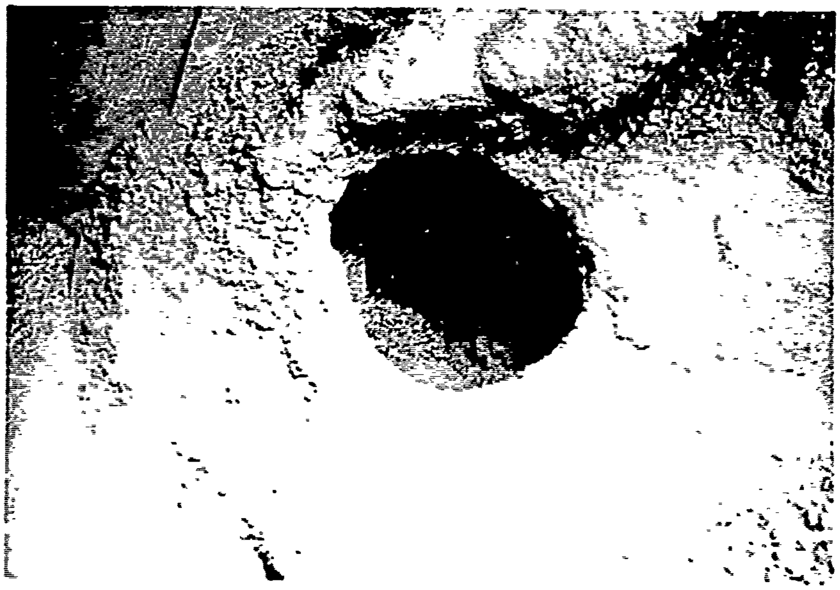


Figure A4. Stable rathole (8 ft [2.4 m] diameter) formed in coal storage bunker when pelletized fluff RDF was stored. No-flow condition resulted. View from above shows hopper outlet 15 ft (4.5 m) below top of rathole.

Figure A5. Fluff RDF which retained container shape after 24 hours at room temperature under no load.

conveyors carrying coal and RDF will ameliorate this problem; however, the concept of layering RDF on coal by conveyor to achieve adequate mixing between storage and furnace is unproven in the field.

To date, study of the handling of RDF indicates that using RDF at Army installations will require comprehensive redesign and modification or replacement of nearly all existing solid-fuel-handling equipment to move fuel from delivery to the furnace.

Pyrolytic Conversion

Research in the waste-to-energy field has emphasized two categories of conversion processes. The first, combustion, is essentially a rapid oxidation reaction in which heat is liberated (exothermic). Pyrolysis, in contrast, is endothermic. The heat required for reaction is provided either indirectly or by partial oxidation (or other reactions) occurring in the pyrolysis reactor. Currently developing pyrolytic conversion systems aim at producing a gaseous fuel from the destructive distillation of organic constituents of MSW.

The preceding sections indicate that a major technical obstacle to use of RDF in existing small-scale boilers is furnace volume (Figure A6). Simply stated, substitution of a substantially lower grade fuel (a coal-RDF mixture) in a small-scale furnace of fixed volume engenders numerous technical problems, some of which are virtually insurmountable without comprehensive redesign and rebuilding. Fuel content of moisture, volatile matter, fixed carbon, and ash, along with heating value, are all determining factors.

The rapid chemical reactions occurring in a furnance do not always result in liberation of heat. What is commonly labeled "combustion" is actually a very complex phenomenon involving a variety of reactions, of which relatively few are thoroughly understood.

The most important variables at play in the combustion process are well-controlled by mechanical stoking mechanisms. Optimal fuel bed depth on travelling grates varies between 6 and 8 in. (15 and 20 cm) with several combustion zones identifiable. Primary air, usually preheated, is introduced underneath the grate (underfire air) and drawn through the bed by furnace draft. In the oxidation zone near the grate, all available oxygen is consumed, forming carbon dioxide. Besides supplying oxygen to support combustion, underfire air carries heat away from the grate (reducing thermal stress on it) to higher zones in the fuel bed.

In the center of the fuel bed, volatile matter in the fuel is driven off by heat. Carbon dioxide from below passes into a zone of hot, liberated carbon, and some may be reconverted to carbon monoxide. Near the top of the fuel bed is a zone rich in volatile hydrocarbons, carbon monoxide, and carbon dioxide. Secondary (overfire) air is introduced above the bed to provide turbulent mixing in a thermal environment sufficient to cause ignition. Some transient oxygen-free zones may develop and will be the sites of additional thermal decomposition and soot formation.

Required fuel residence time is related to the rate of volatilization and the amount and nature of fixed carbon in the fuel. Volatilization rates are usually very rapid, but because MSW and RDF characteristics are highly variable, volatilization rates can be unpredictable and difficult to control. For example, sustaining proper front arch ignition temperatures when cofiring RDF requires almost constant monitoring and quick operator response. Time required for burnout of fixed carbon is much longer than for fuel volatilization and is a dominant factor in determining fuel residence time and plant energy economy.

An inherent advantage of pyrolysis as it is currently being developed is that it removes the point of fuel volatilization to outside the combustion vessel. The product of pyrolytic conversion is a transportable, storable gaseous fuel consisting mainly of lighter hydrocarbons and having up to 30 percent the heating value of natural gas. Byproducts of pyrolysis are more easily manageable ash and residue which, when quenched, develop into glassy frits which can either be landfilled with little environmental adversity or be used in applications such as bituminous road pavings. The major advantage of pyrolysis lies in production of a gaseous phase of RDF which can be upgraded by standard chemical engineering methods to a more controllable supplementary boiler fuel whose use in an existing boiler would require much fewer combustor and fuel-handling hardware alterations than use of any solid phase RDF.

The disadvantage of pyrolytic systems is that a substantial portion of the MSW fuel value is not recovered; the fixed carbon remains in the char, often

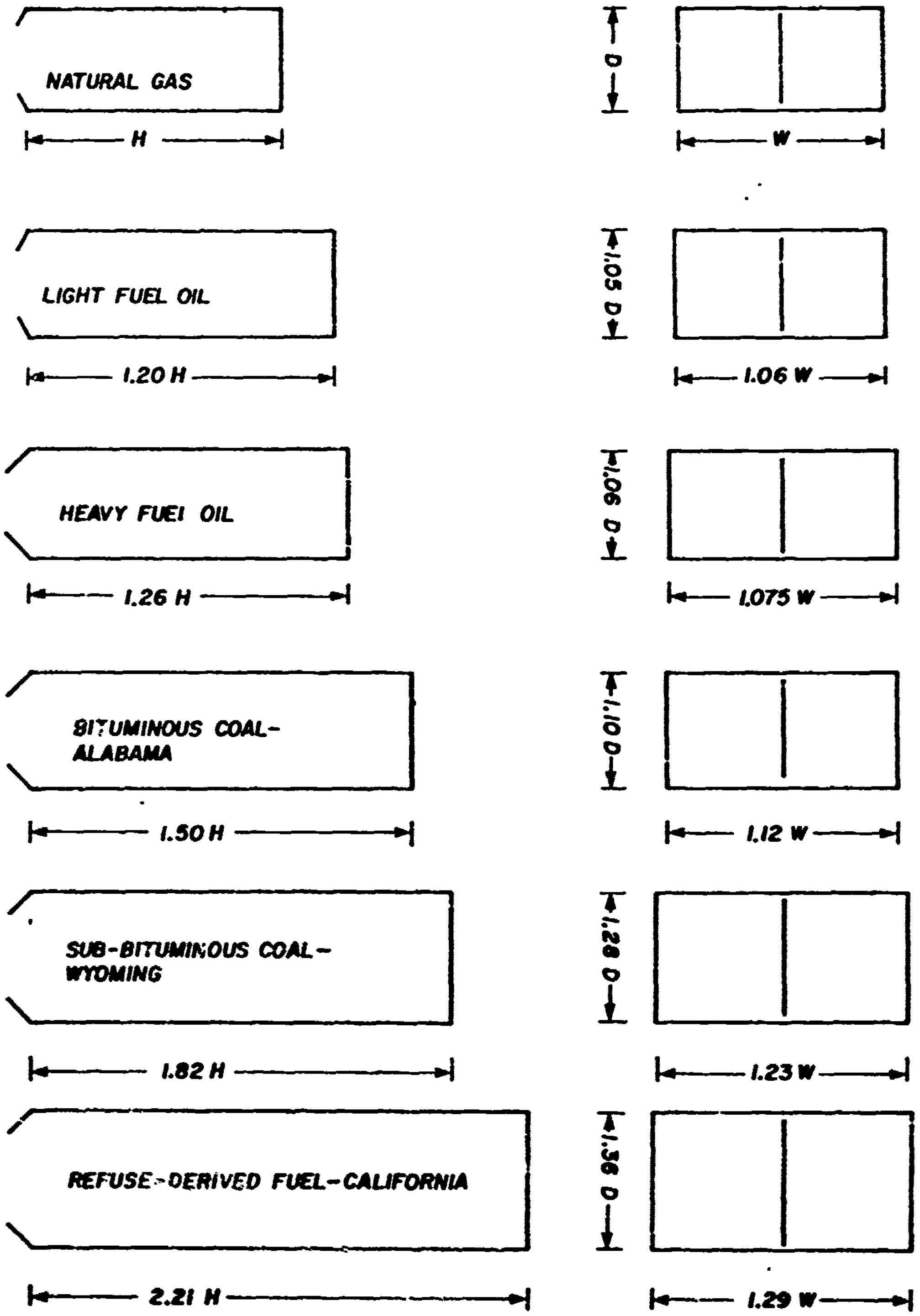


Figure A6. Relative furnace sizes for natural gas, oil, coal, and RDF. (Illustration based on suspension-firing, constant rating.)

undergoing only incomplete oxidation, thus liberating less of the heat required to drive the distillation process than would maximally be possible.

Conclusions

Although use of processed solid waste as a supplementary fuel in Army-scale boilers is a promising topic for research and development, there are many technical questions which must be satisfactorily answered before RDF use in existing boilers can be considered practicable. RDF has not yet been proven to be a universally implementable technology available to help fulfill Army steam production requirements. Lack of long-term operational data makes prediction and guarantee of the performance of any RDF concept design highly speculative. Practicable solutions to the problems discussed above must be found before use of RDF in existing boilers will not entail large risk of boiler mission.

APPENDIX B:

MAJOR ENERGY-RECOVERY PLANTS IN CONUS*

RDF Facilities

Location	Process	Output	Announced Tonnage	Announced Capital Costs (millions of $)	Status
Akron, OH	Shredding; air classification; magnetic separation; burning of RDF product in semi-suspension stoker grate boiler	Steam for urban heating and cooling and industrial use; magnetic metals	1000 tons per day (TPD)(907 MTPD)	25.4	Bids received in September 1975; in process of preparing bond prospectus
Ames, IA	Bailing (waste paper); shredding; magnetic separation; air classification; screening; other mechanical separation	RDF for use by utility; baled paper; magnetic metals; aluminum and other nonmagnetic metals	200 TPD (181 MTPD) 50 tons/hr (45 MT/hr)	5.6	Operational
Baltimore County, MD	Shredding; air classification; magnetic separation	RDF; magnetic metals	600-1500 TPD (544-1361 MTPD)	8.4	Shredding, magnetic separation & land filling operational
Bridgeport, CT	Shredding; magnetic separation; air classification; froth flotation	Dust RDF (powdered fuel) for use in utility boiler, magnetic metals; nonmagnetic metals; glass	2200 TPD (1995 MTPD)	52	Final contract signed; to be operational in 1978
Brockton, MA	Shredding; air classification; magnetic separation; other mechanical separation	Dust RDF for industrial boiler; magnetic metals	400 TPD (363 MTPD)	10-12	Expanded 400 TPD plant under construction; to be completed in 1977
Chicago, IL	Shredding; air classification; magnetic separation	RDF for use by utility; magnetic metals	1000 TPD (907 MTPD)	19	Under construction; shakedown to begin in late 1976
Hempstead, NY	Hydrasposal™ (wet pulping); magnetic and mechanical separation; burning of RDF product in stoker boiler	Electricity; color sorted glass; aluminum magnetic metals	2000 TPD or 150 ton/hr (1814 MTPD or 136 MT/hr)	73	Under construction; operational in 1978
Milwaukee, WI	Shredding; air classification; magnetic and other mechanical separation	RDF for use by utility; bundled paper and corrugated; magnetic metals; aluminum; glass concentrate	1200-1600 TPD (1088-1451 MTPD)	18	Under construction; to start in late 1976
Monroe County, NY	Shredding; air classification; magnetic and other mechanical separation; froth flotation	RDF for use by utility; magnetic metals; nonmagnetic metals; mixed glass	2000 TPD (1814 MTPD)	29	Bids issued for construction in Spring 1976
New Orleans, LA	Shredding; air classification; magnetic and other mechanical separation; hand-picking (paper)	Paper; magnetic metals; aluminum and other nonmagnetic metals; glass	650 TPD (590 MTPD)	6	Start-up ceremony for shredding/landfilling phase July 20, 1976; full recovery operation to begin early 1977

---

*Information provided by National Center for Resource Recovery, Washington, DC.

Location	Process	Output	Announced Tonnage	Announced Capital Costs (millions of $)	Status
Palmer Township, PA	Shredding; air classification; magnetic and other mechanical separation	Densified RDF; magnetic metals; nonmagnetic metals	160 TPD (approx. 30 ton/hr)(145 MTPD or 27 MT/hr)	3.5	Grant received from Pa. Dept. of Environmental Resources; construction expected to begin Spring 1977
St. Louis, MO	Shredding; air classification; magnetic separation; "nuggetizing"	RDF for use by utility; magnetic metals; mixed metals (aluminum and other nonmagnetic)	8000 TPD (7256 MTPD)	70	Advanced planning stage
Saugus, MA	Waterwall incineration; magnetic separation	Steam for industrial use; magnetic metals	1200 TPD (two boilers with 600-TPD capacity each) (1088 MTPD)	35	Operational
Toledo, OH	Shredding; air classification; magnetic separation	RDF; magnetic metals	1000 TPD (907 MTPD)	Unknown	Under design
Pyrolysis Processes					
Baltimore, MD	Landgard® process: shredding, pyrolysis, water quenching, magnetic separation	Steam; magnetic metals; glassy aggregate	1000 TPD (907 MTPD)	EPA-7; State of Maryland-4; City of Baltimore-11; Monsanto-4	In shakedown stage
San Diego County, CA	Shredding; air classification; magnetic and other mechanical separation; froth flotation; pyrolysis	Pyrolytic oil; magnetic and nonmagnetic metals; glass	200 TPD (181 MTPD)	EPA-4.3; San Diego County-2; Petroleum-8.2	Construction underway; to start up in Jan. 1977
South Charleston, WV	Purox™ oxygen converter (pyrolysis); shredding	Fuel gas	200 TPD (181 MTPD)	Unknown	Operational demonstration plant
Anaerobic Digestion Processes					
Pompano Beach, FL	Shredding; air classification; magnetic separation; anaerobic digestion of air-classified light fraction with sewage sludge	Methane	50-100 TPD (45-91 MTPD)	3	"Proof-of-concept" plant in design stage; site preparation to begin August 1976; start-up set for July 1977
Mass Burning					
Nashville, TN	Incineration	Steam for urban heating and cooling	720 TPD (653 MTPD)	26.5	Operational
Norfolk, VA	Incineration	Steam for heating and cooling	180 TPD (163 MTPD)	2.2	Operational

Planned Programs for Methane Recovery From Landfills

Palos Verdes, CA—Los Angeles County Sanitation District; Reserve Synthetic Fuels, Inc. (joint venture of Reserve Oil & Gas Co. and NRG, Inc.)—Operational

Mountain View, CA—City of Mountain View; EPA; Pacific Gas & Electric Co.; Easley & Brassy Co.— Groundbreaking set for Fall 1976; operation to commence early 1977

Projects for the Following Cities in Request for Proposal Stage

Berlin, CN
Beverly, MA
Cuyahoga Valley, OH
Dade County, FL
State of DE
Detroit, MI
Fairmont, MN
Haverhill, MA
Lane County, OR
Newark, NJ
Seattle, WA

CERL DISTRIBUTION

Picatinny Arsenal
ATTN: SMUPA-VP3

Director of Facilities Engineering
APO New York 09827
APO Seattle, WA 98749

DARCOM STIT-EUR
APO New York 09710

USA Liaison Detachment
ATTN: Library
New York, NY 10007

West Point, NY 10996
ATTN: Dept of Mechanics
ATTN: Library

HQDA (SGRD-EDE)

Chief of Engineers
ATTN: Tech Monitor
ATTN: DAEN-ASI-L (2)
ATTN: DAEN-FEB
ATTN: DAEN-FEP
ATTN: DAEN-FEU
ATTN: DAEN-FESA
ATTN: DAEN-FEZ-A
ATTN: DAEN-MCZ-S
ATTN: DAEN-RDL
ATTN: DAEN-PMS (7)
for forwarding to
National Defense Headquarters
Director General of Construction
Ottawa, Ontario K1A0K2
Canada

Canadian Forces Liaison Officer (4)
US Army Mobility Equipment
Research and Development Command
Ft Belvoir, VA 22060

Div of Bldg Research
National Research Council
Montreal Road
Ottawa, Ontario, K1A0R6

Airports and Const. Services Dir.
Technical Information Reference
Centre
KAOL, Transport Canada Building
Place de Ville
Ottawa, Ontario Canada K1A0N8

USA-CRREL

USA-WES
ATTN: Concrete Laboratory
ATTN: Library

Ft Belvoir, VA 22060
ATTN: Kingman Building, Library

Ft Monroe, VA 23651
ATTN: ATEN
ATTN: ATEN-FE-U

Ft Lee, VA 23801
ATTN: DRXMC-D (2)

US Army Foreign Science & Tech Center
ATTN: Charlottesville, VA 22901
ATTN: Far East Office

6th US Army
ATTN: AFKC-LG-E

US Army Engineer District
New York
ATTN: Chief, NANEN-E
ATTN: Chief, Design Br.
Buffalo
ATTN: Library
Pittsburgh
ATTN: Library
ATTN: Chief, Engr Div
Philadelphia
ATTN: Chief, NAPEN-D
Baltimore
ATTN: Chief, Engr Div
Norfolk
ATTN: Library
ATTN: Chief, NAOEN-M
Huntington
ATTN: Library
ATTN: Chief, ORHED

US Army Engineer District
Wilmington
ATTN: Chief, SAWEN-PP
ATTN: Chief, SAWEN-D
Charleston
ATTN: Chief, Engr Div
Savannah
ATTN: Library
ATTN: Chief, SASAS-L
Mobile
ATTN: Chief, SAMEN-C
Nashville
ATTN: Library
Vicksburg
ATTN: Chief, Engr Div
Louisville
ATTN: Chief, Engr Div
Detroit
ATTN: Library
St. Paul
ATTN: Chief, ED
Rock Island
ATTN: Library
ATTN: Chief, Engr Div
Chicago
ATTN: Chief, NCCPD-ER
St. Louis
ATTN: Library
ATTN: Chief, ED-B
ATTN: Chief, ED-D
Kansas City
ATTN: Library (2)
ATTN: Chief, Engr Div
Omaha
ATTN: Chief, Engr Div
New Orleans
ATTN: Library
ATTN: Chief, LMNED-DG
Little Rock
ATTN: Chief, Engr Div
Tulsa
ATTN: Library
Fort Worth
ATTN: Library
ATTN: Chief, SWFED-D
ATTN: Chief, SWFED-MA/MR
Albuquerque
ATTN: Library
Los Angeles
ATTN: Library
San Francisco
ATTN: Chief, Engr Div
Sacramento
ATTN: Library, Room 8307
ATTN: Chief, SPKED-D
Far East
ATTN: Chief, Engr Div
Japan
ATTN: Library
Portland
ATTN: Library
Seattle
ATTN: Chief, NPSEN-PL-WC
ATTN: Chief, NPSEN-PL-ER
Walla Walla
ATTN: Library
ATTN: Chief, Engr Div
Alaska
ATTN: Library
ATTN: Chief, NPADE-R

US Army Engineer Division
Europe
ATTN: Technical Library
New England
ATTN: Library
ATTN: Chief, NEDED-T
North Atlantic
ATTN: Library
ATTN: Chief, NADEN-T
Middle East (Rear)
ATTN: MEDED-T
South Atlantic
ATTN: Chief, SAEN-TE
ATTN: Library
Huntsville
ATTN: Library (2)
ATTN: Chief, HNDED-SR
ATTN: Chief, HNDED-CS
ATTN: Chief, HNDED-ME
Lower Mississippi Valley
ATTN: Library
Ohio River
ATTN: Laboratory
ATTN: Library
ATTN: Chief, Engr Div

US Army Engineer Division
North Central
ATTN: Library
ATTN: Chief, Engr Div
Missouri River
ATTN: Library (2)
ATTN: Chief, Engr Div
ATTN: Laboratory
Southwestern
ATTN: Library
ATTN: Chief, SWDED-TM
South Pacific
ATTN: Chief, [illegible]D-TG
Pacific Ocean
ATTN: Chief, PODED-D
ATTN: Chief, PODED-P
ATTN: Chief, PODED-MP
ATTN: Chief, Engr Div
North Pacific
ATTN: Chief, Engr Div

Facilities Engineer
Carlisle Barracks, PA 17013
Ft Hood, TX 76544
FORSCOM
Ft Devens, MA 01433
Ft George G. Meade MD 20755
Ft McPherson, GA 30330
Ft Sam Houston, TX 78234
Ft Carson, CO 80913
Ft Lewis, WA 98433
USAECOM
Ft Monmouth, NJ 07703
TRADOC
Ft Dix, NJ 08640
Ft Belvoir, VA 22060
Ft Lee, VA 23801
Ft Gordon, GA 30905
Ft McClellan, AL 36201
Ft Knox, KY 40121
Ft Benjamin Harrison, IN 46216
Ft Leonard Wood, MO 65473
Ft Sill, OK 73503
Ft Bliss, TX 79916
USATCFE
Ft Eustis, VA 23604
DSCPER
West Point, NY 10996
USAIC (3)
Ft Benning, GA 31905
USAAVNC
Ft Rucker, AL 36361
CAC&FL (2)
Ft Leavenworth, KS 66027
AMC
Dugway, UT 84022
USACC
Ft Huachuca, AZ 85613
HQ, 1st Inf Div & Ft Riley, KS 66442
HQ, 7th Inf Div & Ft Ord, CA 93941

AF/PREEU
Bolling AFB, DC 20332

AF Civil Engr Center/XRL
Tyndall AFB, FL 32401

Little Rock AFB
ATTN: 314/DEEE (Mr. Gillham)

Kirtland AFB, NM 87117
ATTN: Technical Library (SUL)

Naval Facilities Engr Command
ATTN: Code 04
Alexandria, VA 22332

Port Hueneme, CA 93043
ATTN: Library Code (L08A)
ATTN: Moreell Library

Washington, DC
ATTN: Bldg Research Advisory Board
ATTN: Transportation Research Board
ATTN: Library of Congress (2)
ATTN: Federal Aviation Administration
ATTN: Dept of Transportation Library

Defense Documentation Center (12)

Engineerin Societies Library
New York, NY 10017